

Cosmic Rays in Magnetospheres of the Earth and other Planets





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Lev Dorman

Cosmic Rays in Magnetospheres of the Earth and other Planets



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Dedicated to the memory of my teachers both in science and in life: Professor, Academician Eugenie Lvovich Feinberg (in the former USSR, Physical Lebedev Institute) and Minister of Science of State Israel, Director of Advanced Study Institute of Tel Aviv University, President of Israel Space Agency, Professor Yuval Ne'eman



Eugenie Lvovich Feinberg (1912–2005)

Yuval Ne'eman (1925–2006)

Preface

The problem of cosmic ray (CR) geomagnetic effects came to the fore at the beginning of the 1930s after the famous expeditions by J. Clay onboard ship (*Slamat*) between the Netherlands and Java using an ionization chamber. Many CR latitude expeditions were organized by the famous scientists and Nobel Laureates R. Millikan and A. Compton. From the obtained latitude curves it follows that CRs cannot be gamma rays (as many scientists thought at that time), but must be charged particles. From measurements of azimuthally geomagnetic effect at that time it also followed that these charged particles must be mostly positive (see Chapter 1, and for more details on the history of the problem see monographs of Irina Dorman, M1981, M1989).

The first explanations of obtained results were based on the simple dipole approximation of the geomagnetic field and the theory of energetic charged particles moving in dipole magnetic fields, developed in 1907 by C. Störmer to explain the aurora phenomenon. Let us note that it was made about 5 years before V. Hess discovered CRs, and received the Nobel Prize in 1936 together with K. Anderson (for the discovery of CR and positrons in CR). Störmer's theory, based only on the first, dipole harmonic of the earth's internal magnetic field, played an important role for many years in the explanation of the basic properties of CR geomagnetic effects (see Chapter 2), and is usually used even today for rough estimations of geomagnetic cutoff rigidities and behavior of trapped radiation in the earth's magnetosphere. This theory, developed by G. Lemaitre and M.S. Vallarta, extended the conception of Störmer's cone of forbidden trajectories and introduced the conception of CR allowed cone with the existence of a penumbra region between these cones. From Störmer's theory it follows, for example, that minimal CR intensity line on the earth, so-called CR equator, must coincide with the geomagnetic equator in dipole approximation. However, detailed experimental investigations of CR latitude effect along different meridians show that there are sufficient differences between CR and geomagnetic equators caused by important influence of higher harmonics of the geomagnetic field on CR energetic particles moving in that geomagnetic field. Moreover, besides internal sources of the geomagnetic field also are important external sources caused by different currents in the earth's magnetosphere.

Several analytical and numerical methods for CR trajectory calculations were developed for determining cutoff rigidities for vertical and oblique directions at different zenith and azimuth angles, effective and apparent cutoff rigidities, effective asymptotic directions, impact zones, and acceptance cones in the real geomagnetic field including the higher harmonics (see Chapter 3). This chapter is based not only on original papers of the author and his colleagues N.G. Asaulenko, V.S. Smirnov, and M.I. Tyasto, but also on key works of P. Bobik, E.O. Flückiger, M. Kodama, I. Kondo, K. Kudela, K.G. McCracken, J.J. Quenby, E.C. Ray, M.A. Shea, D.F. Smart, M. Storini, I. Usoskin, W.R. Webber, G.J. Wenk, and many others who calculated these important parameters for CR behavior in the earth's magnetosphere. Especially important are calculations during 1960–1970s of effective cutoff rigidities for vertical direction and effective asymptotic directions for all CR stations of the worldwide network by K.G. McCracken, M.A. Shea, and D.F. Smart (McCracken et al., M1962, M1965; Shea et al., M1965, M1976; Shea and Smart, M1975). M.A. Shea and D.F. Smart also regularly published articles every 5 years, starting from the epoch 1955.0 up to the present time, on data regarding 5° latitude $\times 15^{\circ}$ longitude world grids of trajectory-derived effective vertical cutoff rigidities.

Theoretical results obtained in Chapter 3 were checked in many CR latitude surveys during the Japanese expeditions during 1956-1962 to Antarctica; in Swedent-USA latitude surveys during 1956-1959 in connection with International Geophysical Year; in Canadian expeditions during 1965-1966; in neutron monitor surveys in the Southern Ocean by USA, South Africa, and Australia; in latitude surveys of environmental radiation and soft secondary CR components by Italian expeditions to Antarctica; in annual CR latitude summer surveys over the territory of the former USSR during 1964–1982; in CR planetary surveys by USSR expeditions on the ships Kislovodsk and Academician Kurchatov; in South African latitude surveys on different altitudes from airplanes; and many CR latitude surveys on balloons and satellites (see Chapter 4). In this chapter we consider also: (1) the problem on CR latitude knee mainly in the frame of the key works by O.C. Allkofer and W.D. Dau, (2) CR latitude-altitude dependencies in the frame of the key work by A.V. Belov and colleagues, and (3) daily CR intensity dependencies from cutoff rigidity in the frame of key works by F. Bachelet and colleagues. Let us note that experimental data obtained in many CR expeditions during about 80 years are unique because the geomagnetic field changes sufficiently with time and consequently causes changes in planetary distributions of cutoff rigidities, asymptotic directions, and acceptance cones.

An example of detail analysis of CR latitude survey data obtained in the Italian expedition to Antarctica during 1996–1997 taking into account many different data, exact corrections on meteorological factors, CR worldwide variations, CR North–South and Forward–Backward asymmetries, exact account of oblique CR arriving in calculations of apparent cutoff rigidities along the latitude survey, and some other exact corrections are described in Chapter 5 based mainly on original works of Dorman and his colleagues O.A. Danilova, N. Iucci, M. Parisi, N.G. Ptitsyna, M.I. Tyasto, and G. Villoresi. This analysis made possible the finding of coupling functions for standard neutron monitors and for neutron counters without lead with the highest accuracy at present time.

Preface

Geomagnetic time variations of CR intensity (caused by variations of cutoff rigidities) are determined by internal and magnetospheric sources (see Chapter 6). This chapter considers the trajectory calculations of long-term variations of planetary distribution of cutoff rigidities caused mainly by internal source during the last 2,000 years, during 1600-2000 in steps of 50 years, and during 1950-2005 in steps of 5 years based mainly on key papers of M.A. Shea, D.F. Smart, and E.O. Flückiger. CR geomagnetic variations of magnetospheric origin were discovered in detailed investigations of CR Forbush-decreases during the main phase of great magnetic storms, when at middle latitude stations CR intensity increase caused by decrease of cutoff rigidity was observed. Through many investigations it was established that this decrease of cutoff rigidity is mainly caused by sufficient increase of ring current from about 10^6 A in quiet periods up to about 10^7 A during the main phase of a strong geomagnetic storm (the same phenomenon caused moving of aurora boundary to low latitudes, up to Egypt, in periods of big magnetic storms). CR variations of magnetospheric origin were investigated in detail theoretically and experimentally in key papers by H. Debrunner, E.O. Flückiger, M. Kodama, S. Kudo, T. Makino, T. Obayashi, P. Tanskanen, M.A. Shea, D.F. Smart, and M. Wada, as well as in papers of Dorman and his colleagues L.G. Asaulenko, L.M. Baisultanova, A.V.Belov, V.M. Dvornikov, V. Sdobnov, A.V. Sergeev, M.I. Tyasto, and V.G. Yanke. This chapter also shows that by using CR data inverse problems and estimated time variations of main parameters of ring current and other magnetospheric current systems during big magnetic storms may be solved.

In the last 20 years sufficient jumps were made in our understanding of the earth's magnetospheric structure for different disturbance levels, thanks to key papers by N.A. Tsyganenko and his colleagues M.I. Sitnov and A.V. Usmanov, who developed magnetospheric models on the basis of a lot of satellite and ground observation data. The main matter of Chapter 7 is based on crucial results of Tsyganenko and on key papers which checked these results, and some other magnetospheric models by galactic and solar CR observations (see Contents and References for Chapter 7).

In Chapter 8 we consider very short atmospheric and magnetospheric effects of CR in other planets. It is a pity that this problem up to now is only weakly developed. We do not find any papers in scientific literature devoted to the problem of CR behavior in atmospheres and magnetospheres of other planets and satellites, except two papers of Dorman and colleagues which consider only the planets Venus, Mars, and Jupiter. However, we hope that in the near future this problem will receive higher attention of CR scientists and will be developed to a level comparable with the level of research on our planet.

Let me note, that in this book, as in the previous two (Dorman, M2004 and M2006), I often use extended nomination of CRs as particles with energy much bigger than average energy of background plasma's particles. It means that we have extragalactic CR, galactic CR, solar CR, anomaly CR, interplanetary CR, and magnetospheric CR (there are also outer CR and local CR; for details, see Dorman, M2004, Chapter 1). Scientific literature often uses nomination energetic particles for CRs generated on the sun, in interplanetary space and in magnetospheres of the earth and other planets and their satellites.

The behavior of galactic, solar, and anomaly CRs in the planetary magnetospheres are determined not only by main planetary magnetic fields but also by very variable magnetospheric currents caused by drifts of local CR (energetic particles) in radiation belts and plasma processes from solar wind–magnetosphere interactions as well as interplanetary shock waves–magnetosphere interactions during substorms and magnetic storms. On the other hand, main sources of radiation belts are caused by interactions of galactic, solar, anomaly, and interplanetary CRs with upper atmosphere causing the formation of albedo and acceleration local CRs in many processes inside magnetospheres. So there are really very complicated nonlinear interactions of CR, solar wind, and interplanetary shock waves with planetary magnetospheres.

The detailed Contents give information on the problems considered and discussed in the monograph. At the beginning of this monograph, there is a list of Frequently used Abbreviations and Notations. At the end of the book, in the Conclusion and Problems, we summarize the main results and consider some unsolved key problems, which are important for the development of the considered branch of research. In the References there are separate lists for Monographs and Books (with years starting by the letter M) as well as for each chapter. For the convenience of the reader, we have also prepared a Subject Index. At the end of the book there are Appendices, where we have placed big tables and complicated colored figures; ith labels starting with the letter A.

I would be grateful for any comments, suggestions, preprints, and reprints that can be useful in our future research, and can make the next edition of the book better and clearer. They may be sent directly to me by e-mail (lid@physics.technion.ac.il; lid010529@gmail.com), by fax [+972] 4 696 4952, or by post to the following address: Prof. Lev I. Dorman, Head of ICR&SWC and ESO, P.O. Box 2217, Qazrin 12900, ISRAEL.

July 2008 Qazrin, Moscow, Princeton Lev I. Dorman

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As a sign of my heartfelt gratitude, this book is dedicated to the memory of my teachers, both in science and in life: Eugenie Lvovich Feinberg, in former USSR, and Yuval Ne'eman, in Israel.

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Frequently used Abbreviations and Notations

ACE	Advanced Composition Explorer satellite
a_n^m, b_n^m	Gauss coefficients for planetary magnetic field
CME	coronal mass ejection
CR	cosmic ray
Dst	disturbance storm time index
E	energy of CR particles
E_0	energy of primary CR particle
ESO	Israel–Italian Emilio Segre' Observatory
FAC	field-aligned currents
FEP	Flare Energetic Particles
GLE	ground level event of solar CR increasing
Н	altitude
h	atmospheric pressure
h_o	pressure on the level of observations
IC	ionization chamber, shielded by 10 cm Pb
ICME	interplanetary coronal mass ejections
ICRC	Israel Cosmic Ray Center (1992–2002)
ICR&SWC	Israel Cosmic Ray & Space Weather Center (from 2003)
ICRS	International Cosmic Ray Service (proposed in 1991)
IEF	interplanetary electric field
IGY	International Geophysical Year (July 1957-
	December 1958)
IMF	interplanetary magnetic field
IQSY	International Quiet Sun Year (1964–1965)
L	McIlwain parameter.
MC	magnetic cloud
m w.e.	meters of water equivalent
M_E	magnetic moment of the earth

xxxiv	Frequently used Abbreviations and Notations
$m_i(R, h)$	integral multiplicity: number of secondary CR particles of type <i>i</i> on level <i>h</i> from one primary CR particle with rigidity <i>R</i> on the top of atmosphere
m_o	rest mass of particle
MT	muon or meson telescope

CR intensity

particle rigidity

netic field

radius of the earth

geomagnetic line

solar cosmic rays

solar neutron events

solar energetic particles

solar neutron telescope

vertical air temperature distribution

solar activity

Solar wind

Space weather

neutron monitor or super-monitor

geomagnetic cutoff rigidity

neutron super-monitor of IQSY type

neutron monitor of IGY or Simpson's type

the curve's radius of particle in the dipole mag-

the equatorial distance from the center of the

(here r_c is the radius of the ring current in magne-

tosphere) W(R, h)coupling function Z or θ zenith angle λ latitude: $\theta = \frac{\pi}{2} - \lambda$ the polar angle the polar angle of points of particles return θ_r the angle between magnetic field B and particle ø velocity v longitude, azimuth $\rho = v_{\perp} / \omega_c = \gamma m_o c v \sin \phi / Z e B$ Larmor radius of particle in the magnetosphere $\omega_c = ZeB/\gamma m_o c$ cyclotron frequency

 $N(R_{\rm c}, h)$ or $I(R_{\rm c}, h)$

NM-64 or NM-IQSY

NM

 $R_{\rm C}$

 r_E

 r_{dip}

 r_o

SA

SCR

SEP

SNE

SNT

SW

SW

T(h)

 $u = r_c/r_E$

NM-IGY R = pc/Ze

Chapter 1 First Measurements of Cosmic Ray Geomagnetic Effects and the Problem of CR Nature

1.1 The First Measurements of CR Latitude Effect in Expeditions from Holland to Java and Problems in their Interpretation

Up to the end of the 1920s the common opinion on the nature of cosmic rays (CRs) was that they were high-energy γ -rays. If this were so, the Earth's magnetic field would not have any influence on CR intensity. The geomagnetic effect in CRs was discovered accidentally in 1927 by Dutch researcher J. Clay (1927). For a long time he investigated the time variations and dependence on altitude CR intensity using an ionization chamber on the island of Java. For interpretation of the obtained experimental results. Clay tried to determine background radiation from the material of the ionization chamber, but without any success, and so he decided to make this determination in Holland deep underground. During his journey from Java to Holland on the ship *Slamat*, Clay made several measurements of CR intensity, and to his surprise he found that when approaching the equator the CR intensity decreased by more than 10%. At first, he came to the conclusion that this effect can be explained by possible decrease of γ -emanations in the atmosphere with decreasing latitude. These measurements were repeated many times in the period 1928–1932 during several sea voyages between Java and Holland, and back (Clay, 1928, 1930, 1932; Clay and Berlage, 1932). Figure 1.1 shows these results in comparison with those obtained by other authors using the same type of instruments - shielded by a Pb ionization chamber. The Holland-equator effect was measured with good accuracy: on average $14 \pm 1\%$.

However, the discovered dependence of the CR latitude effect from season to season was very strange: in winter it was bigger than in summer. Also, it was not clear why at latitudes higher than 50° there was no CR intensity increase with an increase in latitude as shown in the following: measurements of CR intensity by F. Begonek in 1928 on the dirigible "Italy" during the first Polar expedition headed by Umberto Nobile (described in Dorman, 1981); negative result obtained by the ionization chamber in the survey from Hamburg to Shpizbergen in 1930



(Bothe and Kolhörster, 1930); and no CR intensity change between Archangelsk ($65^{\circ}N$) and Franz Josef Land ($82^{\circ}N$) observed in 1932 on the icebreaker "Maligin" (Verigo, 1938).

1.2 The First Correct Explanation of CR Latitude Survey Results and Nature of CR; Compton and Millikan's CR Latitude Surveys

The first researchers to give a correct explanation of the Clay effect were Bothe and Kolhörster (1929): they noted that direct information on the nature of CR can be obtained by investigating the influence of the geomagnetic field on CR intensity measured at different geomagnetic latitudes (latitude effect). The existence of this effect discovered in Clay's CR latitude surveys shows that at least some part of a CR must be charged particles. To explain the constant of CR intensity above a latitude of 50° (Kolhörster and Tuwim, 1931), Clay (1932) supposed that primary CRs with rigidity smaller than 4×10^9 V could not reach the earth's surface (caused by the absorption of CRs in the atmosphere). The strong season dependence of the CR latitude effect was explained later by the temperature effect of the CR muon component (Dorman, 1954). The problem of measuring CR geomagnetic effects and their correct interpretation was recognized after a public discussion between two Nobel Prize winners, Robert Millikan (γ -ray hypothesis) and Arthur Compton (charged particle hypothesis) (for details, see Dorman, M1981 and M2004, Chapter 1). On the one hand, no CR latitude effect was observed by Millikan and Cameron (1928) between 19°S (Bolivia) and 34°N (Pasadena, USA), and by Millikan (1930) between 34°N (Pasadena, USA) and 59°N (Churchill, Canada). On the other hand,
in 1932, Compton organized eight expeditions for CR intensity measurements at 69 points at different latitudes and altitudes (see Fig. 1.2).

All measurements in these expeditions were made with the same type of Pb-shielded ionization chambers constructed by Compton (see Fig. 1.3).



Fig. 1.2 The position of the main points where CR intensities were measured during eight Compton expeditions in 1932 (According to Compton, 1932, 1933)







Results of CR measurements at sea level (total latitude effect about 14%), at altitudes of 2,000 m (effect 22%) and 4,360 m (effect 33%) are shown in Fig. 1.4.

Let us note that in 1928 and 1930, R. Millikan and colleagues obtained negative results on CR latitude effect, but continued these measurements from airplanes in 1933 using ionization chambers (Bowen et al. 1933), and came to the conclusion that the CR latitude effect is real and increased sufficiently with an increase of altitude (see Fig. 1.5).

1.3 The First Determination of Planetary Distribution of CR Intensity at Sea Level; Longitude Geomagnetic Effect

Many CR latitude surveys (Clay, 1934; Johnson and Read, 1937; Compton, 1937) were carried out a few years after the famous discussion between Millikan and Compton on the nature of CRs at the end of 1932, and stimulated the development of research into CR geomagnetic effects. It became clear that investigation of CR geomagnetic effects (latitude and longitude) could give the answer to this key problem:



Fig. 1.5 Comparison of CR measurements by the ionization chamber taken from airplane flights at March Field (34° N), Panama (9° N), and Peru ($12-17^\circ$ S) (According to Bowen et al., 1933)



Fig. 1.6 The curves of equal CR intensity (in ion $cm^{-3} sec^{-1}$ – figures on curves) over the whole world (According to Compton, 1936)

What is the main part of a CR, charged particles or γ -rays? For the first time, on the basis described above, and with the results of eight CR expeditions organized by Compton, and measurements made after this, the planetary distribution of CR intensity at sea level all over the world (see Fig. 1.6) was found by Compton (1936). From

Fig. 1.6 it can be seen that: (1) CR intensity mostly depended on not geographic latitudes, but on geomagnetic latitudes (the earth's magnetic dipole is inclined at about 11° to the earth's axis of rotation); (2) there is not only the latitude CR effect, but also the longitude CR effect (CR intensity sufficiently changed along geomagnetic latitudes; in the region of the geomagnetic equator, a minimum of CR intensity is observed in the Indian Ocean). Let us note that the existence of the longitude CR effect was first mentioned by Clay in 1932; he explained this effect by the displacement of the magnetic dipole more than 300 km from the earth's center in the direction of the Indian Ocean.

1.4 The First Measurements of the CR Latitude Effect in the Stratosphere

From Fig. 1.4 it can be seen that the amplitude of the CR latitude effect increased sufficiently with increasing altitude (from 14% at sea level up to 33% at altitude 4,360 m). So the expected CR latitude effect in the stratosphere must be much bigger. The first measurements of CR intensity in the stratosphere were made by S. N. Vernov, who in 1934 developed a special method of receiving CR and meteorological data from balloons by radio. It was found that CR intensity at an altitude of 12 km over Leningrad at latitude 56°N is 2.5 times bigger than at the same altitude over Yerevan at 35°N (Vernov, 1937). During the survey onboard the ship *Sergo* from the Black Sea to the Far East in 1937, CR intensity was measured on balloons at many points; it was found that over the equator region the CR intensity in the stratosphere is about four times smaller than over Leningrad (Vernov, 1938). On the basis of these measurements, Vernov (1939) came to the conclusion that at least 90% of primary CRs are charged particles (and it was possible approximately to determine their energy spectrum).

A lot of CR intensity measurements with ionization chambers on balloons at many latitudes were made in 1937 by Bowen et al., (1937, 1938). Based on the obtained results, they came to the conclusion that in the stratosphere CR intensity changes about three times with latitude (see Fig. 1.7). The four curves shown in Fig. 1.7 are strictly comparable, since the flights were all made using essentially identical thin-walled electroscopes (0.5 mm of steel). The whole instrument, with accessories, weighs but 1,400 g. In a number of cases, the flights at different latitudes were made using the same instrument.

1.5 East–West CR Geomagnetic Effect and Determination of the Sign of Primary Charged Particles

From the above-described investigations of latitude and longitude CR geomagnetic effects, it became clear that most primary CRs are charged particles. However, what is the sign of these particles? The matter of the problem is that the latitude CR



geomagnetic effect is the same for positive and negative particles (it is also true for longitude CR geomagnetic effect). The possibility of using the geomagnetic field to determine the sign of primary CR charged particles was indicated for the first time by Rossi (1931): he noted that if primary CRs contain a non-equal number of positive and negative particles, the intensity from West and East will be different; the biggest difference will be in the case when primary CRs are mostly particles of the same sign. In 1931 he tried to measure the West-East CR asymmetry at sea level by the first constructed CR telescope based on Geiger-Muller counters and electronic schemes of coincidences, but within the frame of statistical errors, no difference in CR intensity from East and West was observed (this experiment is described in Rossi, M1966). The first positive results on measurements of West-East CR asymmetry were obtained in 1933 in Mexico (29°N, 2,250 m above sea level) by Johnson (1933a) and Alvarez and Compton (1933). From the measurements carried out by the telescope on Geiger-Muller counters with axes inclined from the vertical to 45° , it was found that the CR flux from the West is about 10% higher than from the East. A little later in Eritrea at latitude 11°N and an altitude of 2,370 m above sea level, Rossi (1934) measured the West-East CR asymmetry and found that from the West the flux was about 26% higher than from the East. Later the West-East CR asymmetry was measured also on Mt. Alagez in Armenia (35°N): the amplitude of the effect was found to be 9% (Dukelsky and Ivanova, 1935).

By analyzing all data obtained at different latitudes and altitudes, Johnson (1933b) found that the value of West-East CR asymmetry sufficiently increased when approaching the equator: at an altitude of 3,000 m above sea level this asymmetry was only 2% at latitude 48° , 7% at 25° , and 13% at the equator. It was also found that the West-East CR asymmetry sufficiently increased with an increase of altitude: measurements in Peru in the region of the geomagnetic equator showed that at sea level the asymmetry was 7%, but at 4,200 m it was about 16%. On the basis of these measurements, Johnson (1933b) came to the conclusion that almost all primary CRs are positive charged particles. In the framework of CR geomagnetic effects research, Johnson (1938) came to the conclusion that positive charged particles of primary CRs cannot be positrons. Why? Because geomagnetic effects of CR are observed at sea level, under about 1,000 g cm⁻² of air, it means that primary particles with rigidity smaller than 15 GV (or the secondary CR generated in the atmosphere by these primary particles) can reach sea level. However, at about this time, it became well known that positrons with rigidity smaller than 15 GV (or with energy smaller than 15 GeV and their secondary particles and γ -rays) cannot reach sea level. From this it follows that primary CRs must be protons and/or heavier nuclei.

Chapter 2 Cosmic Rays in the Dipole Geomagnetic Field

2.1 Dipole Approximation of Geomagnetic Field and Geomagnetic Equator

2.1.1 Polar Aurora and Störmer's Theory

The foundation and development of the theory of charged energetic particles moving in the magnetic field of the earth came about through the need to explain some geophysical phenomena. These investigations were initiated by C. Störmer (1907), who by researching charged energetic particles moving in the earth's magnetic field, tried to understand the nature of the polar aurora phenomenon. The earth's magnetic field may be presented for a first approximation as a field produced by a dipole with a moment $M_{\rm E} = 8.1 \times 10^{25} \,{\rm Gs.cm}^3$ inclined at 11.5° to the earth's rotation axis and shifted by 342 km relative to the earth's center (according to the magnetic survey of 1944). Störmer (1907, 1931, M1955) based his theory on the dipole approximation of the earth's magnetic field, which describes the main part of the real geomagnetic field. For a long time Störmer's theory was also applied to the investigation of the behavior of charged particles of CRs in the earth's magnetic field. Until now this theory has not lost its interest because many effects of CRs in the geomagnetic field (latitude and East-West geomagnetic effects, cutoff rigidities, penumbra, formation of radiation belts, and others) are the same as in a real field and the difference is only quantitative.

2.1.2 Equations for Particle Moving in Dipole Field and their Integrals

The equation of relativistic particle with the rest mass m_0 and charge Ze moving in the magnetic field H is

$$\frac{\mathrm{d}(m\mathbf{v})}{\mathrm{d}t} = \frac{Ze}{c} \left(\mathbf{v} \times \mathbf{H} \right), \tag{2.1}$$

L. Dorman, *Cosmic Rays in Magnetospheres of the Earth and other Planets*, Astrophysics and Space Science Library 358,
(c) Springer Science+Business Media B.V. 2009 where

$$m = \frac{m_{\rm o}}{\sqrt{1 - v^2/c^2}},$$
(2.2)

v is the velocity of particle, and *c* is the velocity of light. If the particle moving is considered not in Descartes coordinates but in some other coordinates q_i , we obtain, instead of Eq. 2.1, an equation in the Lagrangian form:

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\partial L}{\partial \dot{q}_i} = \frac{\partial L}{\partial q_i},\tag{2.3}$$

where the Lagrangian function $L(q_i, \dot{q}_i)$ for a particle moving in the magnetic field is

$$L = m_{\rm o}c^2 \left(1 - v^2/c^2\right)^{-1/2} + \frac{Ze}{c} \mathbf{v} \cdot \mathbf{A}.$$
 (2.4)

The vector-potential A is connected with the magnetic field H by the relation $\mathbf{H} =$ rot \mathbf{A} . For the dipole magnetic field

$$\mathbf{A} = \frac{\mathbf{M}_{\mathbf{E}} \times \mathbf{r}}{r^3},\tag{2.5}$$

where $\mathbf{M}_{\mathbf{E}}$ is the magnetic dipole moment of the earth. For the corresponding choice of coordinate system (spherical or cylindrical) the vector-potential A will be characterized only with one azimuthal component. For example, in the cylindrical coordinate system ρ, z, φ , we obtain

$$A_{\rho} = 0, A_{z} = 0, A_{\varphi} = \frac{M_{\rm E}\rho}{\left(\rho^{2} + z^{2}\right)^{3/2}}.$$
 (2.6)

The general solution of Eq. 2.1 is a system of six functions (integrals) f_k depending on space coordinates **r**, particle velocity **v**, and time *t* as well as six constants C_k :

$$f_k(\mathbf{r}, \mathbf{v}, t) = C_k; \quad k = 1, 2, \dots, 6.$$
 (2.7)

The analytical expressions of integrals $f_k(\mathbf{r}, \mathbf{v}, t)$ can be obtained only in some special cases when the field does not depend on time and depends only on one or two space coordinates. In these cases, integrals do not depend on time and reflect the laws of conservation. The nondependence of the magnetic field on time leads to the law of energy conservation, which can be very easily obtained from Eq. 2.1: multiplying the scalar in this equation by particle velocity \mathbf{v} , we obtain

$$\frac{\mathrm{d}\left(m\mathbf{v}^{2}\right)}{\mathrm{d}t} = 0; \quad mv^{2} = \mathrm{const.}$$
(2.8)

Because during the moving of a charged particle in the constant magnetic field m = const, relativistic particles will move in the same manner as nonrelativistic particles but with the mass *m* determined by Eq. 2.2. So, to make the consideration easier, we will analyze nonrelativistic equations of charged particles moving in a constant



magnetic field. By using the cylindrical coordinate system (see Fig. 2.1), the integral of energy described by Eq. 2.8 will be as follows for the nonrelativistic case:

$$\dot{\rho}^2 + \dot{z}^2 + \rho^2 \dot{\phi}^2 = \text{const.}$$
 (2.9)

The existence of axial symmetry in the case of a dipole field, i.e., nondependence of the magnetic field from the azimuth φ , leads to the law of conservation of momentum component p_{φ} because in this case $\partial L/\partial \varphi = 0$ and we obtain from Eq. 2.3

$$p_{\varphi} = \frac{\partial L}{\partial \dot{\varphi}} = m\rho^2 \dot{\varphi} + \frac{Ze}{c}\rho A_{\varphi} = \text{const.}$$
(2.10)

Let us introduce the Rauss function

$$L_{\rm R} = L - \sum q_{\rm c} p_{\rm c}, \qquad (2.11)$$

where q_c is the derivative from the cyclic coordinate and p_c corresponds to the coordinate momentum of the particle (in the case of the axial magnetic field symmetry, the cyclic coordinate is φ). In cylindrical coordinates, the Lagrangian function *L* described by Eq. 2.4 will be

$$L = \frac{m}{2} \left(\dot{\rho}^2 + \dot{z}^2 + \rho^2 \dot{\phi}^2 \right) + \frac{Ze}{c} \rho \dot{\phi} A_{\phi}, \qquad (2.12)$$

and the Rauss function

$$L_{\rm R} = L - \dot{\phi} \frac{\partial L}{\partial \dot{\phi}} = \frac{m}{2} \left(\dot{\rho}^2 + \dot{z}^2 \right) - U, \qquad (2.13)$$

where

$$U = \frac{1}{2m} \left(\frac{p_{\varphi}}{\rho} - \frac{Ze}{c} A_{\varphi} \right)^2; \quad p_{\varphi} = \text{const.}$$
(2.14)

Taking into account the integrals of a moving particle transforms the 3-D problem of particle propagation in the dipole magnetic field into a 2-D problem of particle moving in the meridian plane (ρ , z) in the potential field U:

$$m\ddot{\rho} = -\frac{\partial U}{\partial \rho}; \quad m\ddot{z} = -\frac{\partial U}{\partial z}.$$
 (2.15)

2.2 Principles of Störmer's Theory

For convenience of mathematical research into a charged particle moving in the dipole magnetic field, Störmer introduced a special unit of length (now called the Störmer unit)

$$s = \sqrt{M_{\rm E} Z e / m c v}, \qquad (2.16)$$

and changed in equations of particle moving the differentiation over time *t* on the differentiation over *s* by using relation ds = vdt (let us remember that particle velocity v = const). In this case the integrals described by Eqs. 2.9, 2.10, and 2.15 of particle moving will have the forms

$$\left(\frac{\mathrm{d}\rho}{\mathrm{d}s}\right)^2 + \left(\frac{\mathrm{d}z}{\mathrm{d}s}\right)^2 + \rho^2 \left(\frac{\mathrm{d}\varphi}{\mathrm{d}s}\right)^2 = 1, \qquad (2.17)$$

$$\rho^2 \frac{\mathrm{d}\varphi}{\mathrm{d}s} + \frac{\rho^2}{r^3} = 2\gamma, \qquad (2.18)$$

$$\frac{\mathrm{d}^2 \rho}{\mathrm{d}s^2} = \frac{1}{2} \frac{\partial Q}{\partial r}; \quad \frac{\mathrm{d}^2 z}{\mathrm{d}s^2} = \frac{1}{2} \frac{\partial Q}{\partial z}, \tag{2.19}$$

where

$$Q = 1 - \left(\frac{\rho}{r^3} + \frac{2\gamma}{r}\right)^2. \tag{2.20}$$

Equations 2.16–2.20 make up the basis of Störmer's theory. In the framework of this theory were found a lot of trajectories of charged particles in the field of the magnetic dipole. The easiest trajectories are in the equatorial plane and trajectories crossing the dipole.

The trajectories of particles in the equatorial plane (at $z = 0, r = \rho$) on the basis of Eqs. 2.17–2.20 will be determined by the following equation:

$$\frac{\mathrm{d}\varphi}{\mathrm{d}\rho} = \frac{2\gamma\rho - 1}{\rho\left(\rho^4 - (2\gamma\rho + 1)^2\right)^{1/2}}.$$
(2.21)

Fig. 2.2 Trajectories of charged particles in the equatorial plane in the magnetic field of a dipole at different values of Störmer's constant γ



This equation can be integrated by using elliptic functions. All orbits in the equatorial plane can be separated into two types: finite (corresponding to encroached particles) and infinite (corresponding to particles that have arrived from infinite). Both types of orbits are shown in Fig. 2.2. Finite orbits are periodic with $\gamma \ge 1$; infinite orbits can have any value of γ . Finite and infinite orbits are separated by a cyclic curve with the radius corresponding to s = 1 and characterized by $\gamma = 1$.

The trajectories of particles crossing the center of a dipole were also investigated in detail by Störmer (1907, 1931, M1955) using the numerical solution of equations described above. Each trajectory can be considered as a particle moving in the meridian plane in the potential field Q according to Eq. 2.19, and the rotation of this plane around the dipole axis. Let us consider the angle ω as the angle between the element of the trajectory and the East–West direction (see Fig. 2.1). In this case we obtain

$$\rho \frac{\mathrm{d}\varphi}{\mathrm{d}s} = \cos\omega. \tag{2.22}$$

From Eqs. 2.18 and 2.20, by using Eq. 2.22, we obtain

$$\cos^2 \omega = 1 - Q. \tag{2.23}$$

From Eq. 2.23 it follows that particles can move only in the region of space where 1 > Q > 0, and cannot move in the region of space where Q < 0. Therefore, the line Q = 0 is the boundary between the allowed and forbidden trajectories (see Fig. 2.3).

From Fig. 2.3 it can be seen that the trajectory crossing the center of the dipole does not coincide with the magnetic force line: when approaching near the center, the particle comes close to the force line and achieves a spiral movement around the force line. Simultaneously the particle achieves drift in a direction perpendicular to the magnetic force line (rotation of meridian plane of the trajectory at some value of longitude – angle of demolition). In Fig. 2.4, the asymptotic latitude Λ and longitude Φ of trajectories are shown passing the center of the dipole in dependence of the value of Störmer's constant γ , found by Störmer (1931, M1955) on the basis of numerical calculations of many particle trajectories in the magnetic dipole field.



Fig. 2.4 The asymptotic latitude Λ and asymptotic longitude Φ for charged particles crossing the center of a magnetic dipole depending on Störmer's constant γ (numbers near the points on the curve)

In the general case it can be found that the surface separated allowed and forbidden trajectories in the 3-D space. As we mentioned above, this surface will be determined by the condition Q = 0, or according to Eq. 2.20, by equation

$$\left(\frac{\rho}{r^3} + \frac{2\gamma}{r}\right)^2 = 1. \tag{2.24}$$

The crossings of this surface by the meridian plane at two values of Störmer's constant γ are shown in Fig. 2.5.

From Fig. 2.5 it can be seen that at $\gamma > 1$ the allowed region consists of two separated regions: one starts from about the center of the dipole and is bounded before s = 1 in the equatorial plane; the other starts at s > 1 and extends to infinity.



Fig. 2.5 The allowed and forbidden regions of charged particle moving in the meridian plane at two different values of Störmer's constant γ . Along the abscissa axes, the distance from the center of the earth is given in Störmer's units. The forbidden regions are shown by hatching, and the allowed regions are shown in white

The first region corresponds to the particles captured by the dipole magnetic field, and the second is filled by particles arriving from infinity. It is important to note that at $\gamma > 1$ particles cannot arrive from infinity to the region $s \le 1$.

At $\gamma < 1$, the allowed region also consists of two regions, but now they are connected with a narrow isthmus: this means that particles from infinity can reach the region $s \le 1$. The value $\gamma = 1$ is critical: both allowed regions are separated by one point on the equatorial plane and the achievement of particles from infinity to the region $s \le 1$ becomes impossible.

2.3 Störmer's Cone of Forbidden Trajectories

Let us consider the equation for $\cos \omega$. From Eqs. 2.18 and 2.22 it follows that

$$\cos\omega = \frac{2\gamma}{r\cos\lambda} - \frac{\cos\lambda}{r^2}.$$
 (2.25)

As was shown in Section 2.2, all points r < 1 (r is in Störmer's units of length, see Eq. 2.16) are forbidden for trajectories characterized with $\gamma > 1$. Therefore, from Eq. 2.25 it follows that forbidden directions will be all directions for which at r < 1

$$\cos \omega > \cos \omega_{\rm m} = \frac{2}{r \cos \lambda} - \frac{\cos \lambda}{r^2}.$$
 (2.26)

These forbidden directions are inside the circle cone with the axis directed as East–West and the opening angle

$$\omega_{\rm m} = \arccos\left(\frac{2}{r\cos\lambda} - \frac{\cos\lambda}{r^2}\right),\tag{2.27}$$

determined from Eq. 2.26. From Eq. 2.25 it follows that

$$r = \frac{\cos^2 \lambda}{1 + \sqrt{1 - \cos \omega \cos^3 \lambda}},\tag{2.28}$$

and in usual units of length (using the determination of Störmer's units of length according to Eq. 2.16) this relation for particles with charge Ze can be rewritten as

$$R_{\rm c}(\lambda,\omega) = \frac{ZeM_{\rm E}}{cr_{\rm E}} \frac{\cos^4 \lambda}{\left(1 + \sqrt{1 - \cos\omega\cos^3 \lambda}\right)^2},\tag{2.29}$$

where $R_c(\lambda, \omega)$ is the minimal cutoff rigidity which is necessary so that a particle can achieve the earth's surface on the latitude λ at angle ω to the East–West direction. From Eq. 2.29 it follows that a particle with rigidity smaller than

$$R_{\rm cmax} = \frac{ZeM_{\rm E}}{cr_{\rm E}},\tag{2.30}$$

cannot achieve the earth's surface at any latitude and at any azimuth and zenith angle. For vertical arriving of charged particles at any latitude, the minimal rigidity will be

$$R_{\rm cvert} = \frac{R_{\rm cmax}}{4},\tag{2.31}$$

and for arriving at the equator from the West and zenith angle 90° , the minimal rigidity for positively charged particles will be (for negatively charged particles the expression for the minimal rigidity will be the same, but for particles arriving at the equator from the East at the same zenith angle 90°):

$$R_{\rm cmin} = \frac{R_{\rm cmax}}{\left(1 + \sqrt{2}\right)^2} = \frac{R_{\rm cmax}}{5.84},$$
 (2.32)

For primary protons and the present value of the earth's magnetic dipole, the abovedescribed values will be

$$R_{\rm cmax} = 59.2\,{\rm GV}, R_{\rm cvert} = 14.8\,{\rm GV}, R_{\rm cmin} = 10.2\,{\rm GV}.$$
 (2.33)

In the general case, instead of Eq. 2.29 for protons and the present value of the earth's magnetic dipole, we obtain

2.4 Lemaitre and Vallarta CR Allowed Cones in the Dipole Geomagnetic Field

$$R_{\rm c}(\lambda,\omega) = \frac{59.2\cos^4\lambda}{\left(1 + \sqrt{1 - \cos\omega\cos^3\lambda}\right)^2} \,\mathrm{GV},\tag{2.34}$$

for cutoff rigidity in dependence of latitude λ and angle ω (Störmer's cone), and for vertical arriving ($\omega = 90^{\circ}$) it will be

$$R_{\rm cvert}(\lambda) = 14.8\cos^4\lambda\,{\rm GV}.\tag{2.35}$$

2.4 Lemaitre and Vallarta CR Allowed Cones in the Dipole Geomagnetic Field; Existence of Penumbra Region

In Eq. 2.26 determining Störmer's cone of forbidden trajectories, it was assumed that $\gamma = 1$. Lemaitre and Vallarta (1933), by numerical calculations of a lot of charged-particle trajectories in the dipole magnetic field, show that it is necessary to use equations

$$\cos\omega > \cos\omega_{\rm m} = \frac{2\gamma_{\rm c}}{r\cos\lambda} - \frac{\cos\lambda}{r^2}$$
(2.36)

for the cone of allowed trajectories instead of Eq. 2.26 Störmer's constant γ_c depends on the geomagnetic latitude as shown in Table 2.1.

If Störmer's cone determines the cutoff rigidities that all particles with smaller rigidities will have forbidden trajectories, the main cone introduced by Lemaitre and Vallarta (1933), or allowed cone according to Vallarta (M1938), determines the cutoff rigidities that all particles with bigger rigidities will have allowed trajectories. As can be seen from Table 2.1, only for the equator will both these cones coincide, but for bigger geomagnetic latitudes there is a sufficient difference: the region of rigidities between both cones formed the penumbra that coincides with a lot of allowed and forbidden trajectories. The relative role of penumbra sufficiently increases with an increase of geomagnetic latitude. The function of penumbra f(R) is determined as 0 for forbidden trajectories and 1 for allowed trajectories. The early theoretical investigations of the penumbral effects in the dipole field approximation were summarized by Vallarta (1949) and Schwartz (1959); experimental investigations of these effects were made by Hedgecock (1964, 1965) using terrella experiments.

Table 2.1 Values of Störmer's constant γ_c depending on geomagnetic latitude λ

Geomagnetic latitude λ	0°	10°	20°	30°
Störmer's constant γ_c	1.000	0.978	0.911	0.806

2.5 Drift Hamiltonian for a Dipole Magnetic Field

2.5.1 The Matter of Problem

Nosov and Kyzhyurov (1995) note that, after papers of Gardner (1959), Northrop and Teller (1960) were issued, there was significant interest in the Hamilton formulation of drift theory. In these papers it was shown that the drift equations of the motion of the charged particles captured by the magnetic field look like the Hamilton canonic equations provided they are expressed within the terms of α and β coordinates which are actually Euler's potentials. In the paper by Nosov (1992), the drift Hamiltonian is obtained in the α and β magnetic coordinates. It shows that the Hamiltonian structure is defined by choosing the third *s* parameter. In the paper by Nosov and Kyzhyurov (1995), the curtain expressions for drift Hamiltonian are drawn in the three most important cases by the choice of the *s* parameter. The orthogonal system of coordinates is defined in which the velocity of the cross-drift of the particle is easily calculated from the Hamilton equations. The geometric shapes of the adiabatic zone are found in the dipole magnetic field, where applying the drift Hamiltonian for the description of charged-particle motion is most appropriate.

2.5.2 Drift Hamiltonian

According to Nosov and Kyzhyurov (1995), the magnetic field **B** and the magnetic vector-potential **A**, owing to Euler's potential, can be put down as follows:

$$\mathbf{B} = [\nabla \alpha \times \nabla \beta], \quad \mathbf{A} = \alpha \nabla \beta. \tag{2.37}$$

For the dipole magnetic field, parameters α and β can be expressed through the spherical coordinates *r*, θ , φ by the following relations (Stern, 1976):

$$\alpha = B_0 a_0^2 r^{-1} \sin^2 \theta, \quad \beta = a_0 \varphi, \tag{2.38}$$

where a_0 is the planet's radius, B_0^{\sim} the magnetic field on the equator, and θ and φ polar and azimuthal angles.

By adding the set α and β to the third parameter *s*, it is possible to define them as single-valued functions from spatial coordinates x^j :

$$\xi^{1} = \beta(x^{j}), \quad \xi^{2} = s(x^{j}), \quad \xi^{3} = (q/c)\alpha(x^{j}), \quad (2.39)$$

where *q* charge of the particle, *c* velocity of light. Taking the functions $\xi^i(x^k)$ as curvilinear coordinates, it can define a symmetric contra-variant tensor $g^{ik} = (\nabla \xi^i \cdot \nabla \xi^k)$, and metric tensor g_{ik} . The main term of drift Hamiltonian in coordinates α , β , *s* is obtained as (Nosov, 1992):

$$H(\alpha, s; I) = I\Omega(\alpha, s) + \left(p_s^2/2m\right)g_{22}(\alpha, s) + q\Phi(\alpha, s), \qquad (2.40)$$

where \tilde{I} the first adiabatic invariant, Ω cyclotron frequency, *m* mass of particle, g_{22} the component of metric tensor, Φ electric field potential, and p_s generalized particle moment canonically conjugated with the coordinate *s*.

As a result of the axial symmetry of the dipole magnetic field, coordinate β is a cyclic one, and the components of tensor g^{13} and g^{12} are equal to zero. The components g^{11} and g^{33} for the dipole magnetic field are equal:

$$g^{11} = a_{\rm o}^2 / r^2 \sin^2 \theta, g^{33} = m^2 \Omega_{\rm o}^2 (a_{\rm o} / r)^4 \sin^2 \theta (1 + 3\cos^2 \theta), \quad \Omega_{\rm o} = \frac{|q|B_{\rm o}}{mc}.$$
(2.41)

The other components, g^{22} and g^{23} , and also the components of metric tensor g_{22} and g_{23} can be defined by the choice of parameter *s*.

2.5.3 Three Cases of the Choice of Parameters

Nosov and Kyzhyurov (1995) considered three most important cases of the choice of parameter *s*:

Case I. Usually, parameter *s* is considered to be the length of the magnetic force line. In this case parameter *s* can be expressed in coordinates *r*, θ as follows:

$$s(r,\theta) = r\left(\cos\theta\sqrt{1+3\cos^2\theta} + 3^{-1/2}\ln\left|\sqrt{1+3\cos^2\theta} + \sqrt{3}\cos\theta\right|\right) / 2\sin^2\theta,$$
(2.42)

and the values g_{22} and g^{23} equal as follows:

$$g_{22} = 1, \ g^{23} = \left[-q\alpha(r,\theta) s(r,\theta) + 2q\alpha(r,\theta) \cot an\theta \frac{\partial s}{\partial \theta} \right] / cr^2.$$
(2.43)

In the considered case, the Hamiltonian has the simplest form. In this coordinate system, it is easy to obtain the approximated expression for the second adiabatic invariant J, to the action–angle variables and put down the Hamiltonian as follows:

$$\mathbf{K}(\alpha, IJ) = I\Omega_e(\alpha) + J\Omega_b(I, \alpha), \qquad (2.44)$$

where

$$J = (E - \mathrm{I}\Omega_e) / \Omega_b, \qquad (2.45)$$

and E- total energy of the particle, Ω_e - quatorial cyclotron frequency, Ω_b - frequency of particle oscillation between the mirror points:

$$\Omega_b = \sqrt{\mathrm{I}m^{-1} \mathrm{d}^2 \Omega / \mathrm{d}s^2 + qm^{-1} \mathrm{d}^2 \Phi / \mathrm{d}s^2}.$$
 (2.46)

The results of the second derivatives are defined on the equator. However, it is worthwhile noting that in case I, the system of coordinates is not orthogonal. That is why, in this case, the $\dot{\beta}$ value from the Hamilton equations cannot be defined as the velocity of a transverse drift of particle.

Case II. If you take the angle between direction of magnetic field and equatorial plain as the parameter

$$s(\theta) = \theta + \arctan\left(\frac{1}{2}\tan\theta\right) + \frac{\pi}{2},$$
 (2.47)

for the values which depend on the choice of *s*, it will be

$$g_{22} = r_{\rm c}(\alpha, s), \quad g^{23} \neq 0,$$
 (2.48)

where r_c is the radius of curvature of the magnetic force line. Hamilton's equation

$$\dot{p}_s = -\partial H / \partial s, \tag{2.49}$$

describing the motion of the guiding center of a particle along the magnetic force line, can be easily integrated in this coordinate system. Its solution (when $\Phi = 0$) corresponds to the constancy of the magnetic moment of the particle. This coordinate system, as the preceding one, is not orthogonal and the value $\dot{\beta}$ here also does not correspond to the velocity of the drift of the guiding center across the magnetic force line.

Case III. On the condition that all non-diagonal metric matrix elements equal zero, the orthogonal coordinate system is formed by the choice, as the parameter *s* is the quantity of the scalar potential of magnetic dipole:

$$s = a_o^3 B_o \cos\theta / r^2. \tag{2.50}$$

In this case it will be

$$g_{22} = B^{-2}, \quad g^{23} = 0.$$
 (2.51)

For the drift velocity u_{dr} across the magnetic field, which in this coordinate system is proportional to the value $\dot{\beta}$, Nosov and Kyzhyurov (1995) obtained the well-known expression (Alfvén and Fälthammar, M1963):

$$u_{\rm dr} = \left(\dot{\beta} / a_{\rm o}\right) r \sin \theta = \frac{q}{|q|} \left(\frac{v_{\perp}^2}{2} + v_{||}^2\right) \sin^5 \theta \left(1 + \cos^2 \theta\right) L^2 / a_{\rm o} \Omega_{\rm o}, \qquad (2.52)$$

where $v_{||}$ and v_{\perp} are the velocities of a particle in the longitudinal and transverse direction relative to the magnetic field, respectively; $L = a_0 B_0 / \alpha$ is the McIllwain parameter.

Nosov and Kyzhyurov (1995) note that in case III parameter *s* is the potential, naturally adding the set of Euler's potentials α and β . In this coordinate system, Hamilton's equations describe both the longitudinal and transverse motions of the guiding center. However, the coordinate systems I and II appear to be much more convenient for solving some problems.

2.5.4 The Conditions for Drift Approximation

The coordinate system in case II is convenient for defining the geometric shape in the region of the magnetic dipole, which, when using the drift approximation, is true. The conditions of drift approximation for the transverse and longitudinal particle motions are put down as follows:

$$\left| \left(\mathbf{r}_{\mathbf{g}} \cdot \nabla \right) \mathbf{B} / B \right| = \varepsilon_{\perp} \ll 1, \tag{2.53}$$

$$\left|2\pi \left(\mathbf{v} \cdot \mathbf{B}\right) \left(\mathbf{B} \cdot \nabla\right) \mathbf{B} / B^{3} \Omega\right| = \varepsilon_{\parallel} \ll 1, \qquad (2.54)$$

where $\mathbf{r}_{\mathbf{g}}$ is the Larmor radius. Usually, defining the criterion of adiabaticity for particle moving in the dipole magnetic field the condition is used:

$$|\mathbf{r}_{\mathbf{g}}| \cdot |\nabla \mathbf{B}| / B = \varepsilon \ll 1. \tag{2.55}$$

The critical value of the parameter $\varepsilon = \varepsilon_{cr}$ can be defined either in an experimental way or with the help of numerical simulation. The observations of intensity of trapped radiation decreasing in the magnetosphere with increasing distance from the earth show the critical value $\varepsilon_{cr} = 0.075$ (Singer, 1959). Webber (1963) has found that the divergence between trajectories calculated by the Störmer method and the method of drift approximation becomes considerable when $\varepsilon_{cr} \approx 0.4$. Nosov and Kyzhyurov (1995) considered the drift conditions for the transverse (Eq. 2.53) and longitudinal (Eq. 2.54) motions separately and found the geometry of adiabatic area. The critical values of these parameters $\varepsilon_{\perp cr}$ and $\varepsilon_{||cr}$ are assumed alike and equal to 0.1. Then, from Eqs. 2.53 and 2.54 Nosov and Kyzhyurov (1995) defined four different zones in the mirror-point distribution and on the meridian plane. In Fig. 2.6 these shaded areas are denoted as A, B, C, and D. Both conditions described by Eqs. 2.53 and 2.54 are satisfied for adiabatic area A. In area D, neither condition is satisfied. In area C, there are the points of particle reflection for which only the second condition is broken. In area B only Eq. 2.53 is not satisfied.

For comparison, Fig. 2.6 also plots the curve 1 corresponding to Störmer's forbidden region. The equation of this curve is the following:

$$r/C_{\rm St} = \sin^2\theta / \left(1 + \sqrt{1 + \sin^3\theta}\right), \tag{2.56}$$

2.6 Symplectic Method for the Tracing of CR Particle Motion in a Dipole Magnetic Field

2.6.1 The Matter of Problem

In the paper by Yugo and Iyemori (2001), a new integration technique, the symplectic method, is introduced and applied for tracing CR charged particle motion in a dipole magnetic field. This method is an integral technique for the Hamilton system



Fig. 2.6 Structure of the adiabatic region A, and regions B, C, and D in a dipole magnetic field. Curve 1 corresponds to Störmer's forbidden region. At the bottom there are two L-scales for protons and electrons (According to Nosov and Kyzhyurov, 1995)

using the repetition of canonical transformation, and has been tested in celestial mechanics (Kinoshita et al. 1991; Gladman et al. 1991). Yugo and Iyemori (2001) noted that if the magnetic field is strong enough to trap the energetic charged particle, it becomes possible to separate the motion of a charged particle into Larmor motion and guiding center motion. The motion in a dipole magnetic field has been analyzed with the guiding center approximation by many authors (e.g., Ejiri, 1978). Calculations using the guiding center approximation in a realistic magnetosphere have also been made (e.g., Takahashi and Iyemori, 1989). However, if the electromagnetic fields fluctuate on a time scale comparable to the Larmor period, or if the Larmor radius is comparable to the size of the magnetosphere, or if the curvature of a magnetic field line of interest is not everywhere small compared to the reciprocal Larmor radius, the adiabaticity (i.e., the guiding center approximation) is broken and it is necessary to trace the particle orbit directly.

Yugo and Iyemori (2001) firstly introduced the concept of the symplectic integration. Next, they tested the method by tracing the charged particles in a dipole magnetic field and made an error estimation. Then, the Hamiltonian of the motion of a charged particle in a dipole magnetic field and an "effective potential" were given. They introduced the symplectic integration and its numerical scheme used in this study, and showed the results of calculations by the symplectic method and compared them with those by the standard Runge–Kutta method.

2.6.2 Hamiltonian Description of Energetic Charged Particle Motion in a Dipole Magnetic Field

As was described in Section 2.3, in a dipole magnetic field the motion of an energetic charged particle is classified into trapped and untrapped regions. This motion was first analyzed by Störmer (1907). The dipole magnetic field is represented in a spherical coordinate system with a vector potential

$$A_{\varphi} = -\frac{\mu_{\rm o}M}{4\pi} \frac{\sin\theta}{r^2}.$$
(2.57)

Here, $M = 8 \times 10^{22}$ [Am2], for the earth's dipole moment. According to Yugo and Ivemori (2001), the motion of an energetic charged particle in a dipole magnetic field is written with a Hamiltonian as

$$H = \frac{1}{2m} \left[p_r^2 + \frac{p_\theta^2}{r^2} + \frac{\left(p_\varphi - qrA_\varphi \sin \theta \right)}{r^2 \sin^2 \theta} \right], \qquad (2.58)$$

where p_r , p_{θ} and p_{ϕ} are canonical momenta that correspond to space coordinates r, θ , and φ , respectively, m is the mass, and q is the charge of the particle. The following is the case when the sign of q is positive. For the normalized canonical equations, one can write the Hamiltonian as

$$H = \frac{1}{2} \left[p_r^2 + \frac{p_{\theta}^2}{r^2} + \frac{\left(p_{\varphi} + r^{-1} \sin^2 \theta \right)^2}{r^2 \sin^2 \theta} \right],$$
 (2.59)

where H is a conserved quantity, and by one of the canonical equations, $\dot{p}_{\varphi} = 0$, p_{φ} is another conserved quantity.

Yugo and Iyemori (2001) set H = E and $p_{\varphi} = -C$. From other canonical equations, $\dot{r} = p_r$ and $\theta = p_{\theta}/r^2$, they get

$$v^2/2 + U(r,\theta) = E,$$
 (2.60)

where

$$v^2 = \dot{r}^2 + \left(r\dot{\theta}\right)^2,$$
 (2.61)

and introduced

$$U(r,\theta) = \frac{1}{2r^2\sin^2\theta} \left(\frac{\sin^2\theta}{r} - C\right)^2,$$
(2.62)

as an effective potential (see Fig. 2.7).

Figure 2.8 shows the regions of trapped and untrapped conditions of protons in the earth's dipole magnetic field calculated by Eq. 2.62.

If the starting of the tracing of proton is from region A, the proton is trapped; however, if the starting of the tracing is from region C, the proton is untrapped. In the case when the starting of the tracing of the proton is from region B, the state,



Fig. 2.7 Panels **a** and **b** show the intersection of U at $\theta = \pi/2$ for C > 0 and for C < 0, respectively. The energy level *El* is in the trapped region, and *E*2 and *E*3 are in the untrapped region. Panel **c** is a cartoon for a trapped particle (Larmor motion), and panel **d** is for an untrapped particle (From Yugo and Iyemori, 2001)



Fig. 2.8 The trapped and untrapped regions of protons in the earth's dipole field. Region A is trapped, and region C is untrapped. In region B, the trapped and untrapped states depend on the direction of the initial velocity. In region B, the state, trapping or untrapping, depends on the direction of the initial velocity (From Yugo and Iyemori, 2001)

trapping or untrapping, depends on the direction of the initial velocity (formation of penumbra, see Section 2.4). Yugo and Iyemori (2001) noted that the untrapped particles do not show the Larmor motion anymore.

2.6.3 Symplectic Integration Method of Calculations

Yugo and Iyemori (2001) applied the symplectic integration method to solve the equations of particle motion in the dipole magnetic field. An explicit method exists when the Hamiltonian is separated into the generalized momentum term and the generalized coordinate term (Yoshida, 1993). Investigations have been made to test the method in celestial mechanics, especially in the 2-body problem (Kinoshita et al. 1991; Gladman et al. 1991). However, in the case of charged particles moving in the dipole magnetic field, the two terms cannot be separated, and this explicit method cannot be used; it is necessary to develop a special implicit method (Yugo and Iyemori, 2001).

Let the variables $p = (p_1, p_2, ..., p_n), q = (q_1, q_2, ..., q_n)$ be the canonical variables of a Hamilton system. Mapping $(\mathbf{p}, \mathbf{q}) \rightarrow (\mathbf{p}^*, \mathbf{q}^*)$ is called "symplectic" when

$$\psi'^T \psi' = J \tag{2.63}$$

is satisfied. Here

$$\psi' = \frac{\partial \left(\mathbf{p}^*, \mathbf{q}^*\right)}{\partial \left(\mathbf{p}, \mathbf{q}\right)}, \ J = \begin{pmatrix} O_n & I_n \\ -I_n & O_n \end{pmatrix}, \tag{2.64}$$

and O_n is an *n*th-order zero matrix, and I_n is an *n*th-order unit matrix.

The transformation $(\mathbf{p}(t), \mathbf{q}(t)) \rightarrow (\mathbf{P}(t), \mathbf{Q}(t)) = (\mathbf{p}(t+h), \mathbf{q}(t+h))$ is symplectic (i.e., canonical) and, by Liouville's theorem,

$$d\mathbf{p}(t) \wedge d\mathbf{q}(t) = d\mathbf{p}(t+h) \wedge d\mathbf{q}(t+h).$$
(2.65)

This means that the symplectic mapping is an area-preserving mapping in a $2\tilde{n}$ dimensional plane. The symplectic method is an integration method to keep this condition numerically. The symbol like $dx_1/\langle dx_2 \rangle$ indicates an oriented volume element of $dx_1/\langle dx_2 \rangle$. Here,

$$\mathrm{d}x_1/\backslash\mathrm{d}x_2 = \mathrm{d}x_2/\backslash\mathrm{d}x_1 \tag{2.66}$$

and

$$\int f(x)\mathrm{d}x_1 \wedge \mathrm{d}x_2 = \int f(x)\mathrm{d}x_1\mathrm{d}x_2. \tag{2.67}$$

One of the symplectic-type integral methods is written by the general Runge–Kutta formula shown below, and details are written in Sanz-Serna and Calvo (M1994).

Yugo and Iyemori (2001) considered a set of differential equations

$$\frac{d\mathbf{y}}{dt} = \mathbf{F}(\mathbf{y}) \tag{2.68}$$

and tried to develop y_n with a time step *h*. In this calculation, Eq. 2.68 corresponds to the canonical equations derived from Eq. 2.59. Yugo and Iyemori (2001) chose a set of weights

$$\begin{array}{c}
a_{11} \dots a_{1s} \\
\dots \dots \\
a_{s1} \dots a_{ss} \\
\hline
b_1 \dots b_s
\end{array}$$
(2.69)

and found Y_i (i = 1, ..., s) that satisfied

$$Y_i = y_i + h \sum_{j=1}^{s} a_{ij} F(Y_j).$$
(2.70)

The development of *y* is described as

$$Y_{n+1} = y_n + h \sum_{i=1}^{s} b_i F(Y_i).$$
(2.71)

It is known that if Eq. 2.68 is a set of canonical equations, and if the above set of weights satisfies the condition

$$b_i a_{ij} + b_j a_{ji} - b_i b_j = 0$$
 $(i, j = 1, \dots s),$ (2.72)

this calculation becomes the symplectic method. At a 5-stage, as Eq. 2.69, there are some sets of (a, b) that satisfy Eq. 2.72. The orders of calculations in each selection are over s, and there is a unique choice of (a, b) that achieves the order 2s. The set of (a, b) for the fourth-order method is described as

$$\frac{\begin{vmatrix} \frac{1}{4} & \frac{1}{4} - \frac{\sqrt{3}}{6} \\ \frac{\frac{1}{4} - \frac{\sqrt{3}}{6} & \frac{1}{4} \\ \hline \frac{1}{2} & \frac{1}{2} \end{vmatrix}} (2.73)$$

and that for the sixth-order method as

$$\begin{vmatrix}
\frac{5}{36} & \frac{2}{9} - \frac{\sqrt{15}}{15} & \frac{5}{36} - \frac{\sqrt{15}}{30} \\
\frac{5}{36} + \frac{\sqrt{15}}{24} & \frac{2}{9} & \frac{5}{36} - \frac{\sqrt{15}}{24} \\
\frac{5}{36} + \frac{\sqrt{15}}{30} & \frac{2}{9} - \frac{\sqrt{15}}{15} & \frac{5}{36} \\
\frac{5}{18} & \frac{4}{9} & \frac{5}{18}
\end{vmatrix}$$
(2.74)

To show the advantage of the above method, Yugo and Iyemori (2001) used the standard Runge–Kutta method (fourth order). This method is written as

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$$y_{n+1} = y_n + \frac{h}{6} \left(\mathbf{k}_1 + \mathbf{k}_2 + \mathbf{k}_3 + \mathbf{k}_4 \right),$$
 (2.75)

where,

$$\mathbf{k}_1 = \mathbf{F}(y_n), \quad \mathbf{k}_2 = \mathbf{F}\left(y_n + \frac{h}{2}\mathbf{k}_1\right), \quad \mathbf{k}_3 = \mathbf{F}\left(y_n + \frac{h}{2}\mathbf{k}_2\right), \quad \mathbf{k}_4 = \mathbf{F}(y_n + h\mathbf{k}_3)$$
(2.76)

The above method is described by the general Runge–Kutta formula as

2.6.4 Comparison with the Standard Runge–Kutta Method

Yugo and Iyemori (2001) made a tracing of single proton drift motion having energy from 10 keV to 10 MeV at 5 *re* in the geomagnetic dipole field with fourth- and sixth-order symplectic methods. The pitch angles at the crossing of the equatorial plane were set at several values from 90° to 30°. The time step was about 0.016 of the Larmor period on the equatorial plane and the calculations were made for 10,000,000 steps. For comparison, Yugo and Iyemori (2001) solved the equation of motion

$$m\frac{\mathrm{d}^{2}\mathbf{r}}{\mathrm{d}t^{2}} = q\mathbf{v} \times \mathbf{B}$$
(2.78)

in a spherical coordinate system with the standard Runge–Kutta method (fourth order). Figure 2.9 shows the examples of relative error accumulation in energy with fourth- and sixth-order symplectic methods, S4 and S6, and with the standard Runge–Kutta method, RK4.

The relative error in Fig. 2.9 is defined as

$$\operatorname{error} = |E - E_{o}|/E_{o}, \qquad (2.79)$$

where E_0 is the exact energy and E is the energy in numerical integration. From Fig. 2.9, the advantage of the symplectic method is clear. Although the error for the calculation with the fourth-order symplectic method for pitch angle 30° apparently fluctuates (panels c and d in Fig. 2.9) because of the mirror motion along the dipole magnetic field, the error does not continue to increase. On the other hand, the calculation with the standard Runge–Kutta method soon breaks down. This indicates that, in the calculation using the symplectic method, the numerical error accumulation is much smaller than that with the standard Runge–Kutta method. Yugo and Iyemori (2001) also found that, because of the co-negation of the error, the error



Fig. 2.9 The relative error in energy for protons at 5 *re* with fourth-order symplectic method (S4, fluctuating in panels **c** and **d**), with the sixth-order symplectic method (S6, thick lines), and with the standard Runge–Kutta method (RK4). The energies and the pitch angles of each proton are: in panel a 10 keV, pitch angle 90°; in panel **b** 10 MeV, pitch angle 90°; in panel **c** 10 keV, pitch angle 30° ; in panel **d** 10 MeV, pitch angle 30° (From Yugo and Iyemori, 2001)

development with the fourth-order symplectic method is in the same order as that with the sixth-order symplectic method. The CPU times necessary for the calculation with fourth- and sixth-order symplectic methods are almost the same and, at most, 10 times that with the standard Runge–Kutta method. On the other hand, Yugo and Iyemori (2001) had to set the time step more than 100 times shorter in the calculation with the standard Runge–Kutta method even for the particle with pitch angle 90°. With the standard Runge–Kutta method, it is difficult to trace a proton having a 30° pitch angle at the equatorial plane with any time step.

2.6.5 Main Results and Discussion

Yugo and Iyemori (2001) tested the symplectic integrator in the earth's dipole magnetic field for typical high-energy charged particles in the radiation belt, and showed the advantage of the new method. They believe that this method is useful for the numerical simulation of the earth's or other planets' radiation belts in which the acceleration mechanisms have not been well understood. For example, the formation of the radiation belt under a geomagnetic storm is very peculiar (e.g., Knipp et al., 1998). Some scenarios are considered, but no one has produced a quantitative and satisfactory theory. There must exist some non-adiabatic processes and the described method would be useful to solve the problem. The following point should be noted. In Fig. 2.7 in panel a, the energy level El is the trapped region and the E2 is the untrapped region, and the transition between these two regions is very abrupt. This characteristic can be confirmed by tracing a particle trajectory in a dipole field with a small perturbation, although not shown here. That is, the injection and the escape of high-energy charged particles, such as protons of several hundred million electron volts (see Fig. 2.8), is not gradual, but abrupt. It is necessary to take into account this abrupt transition between these two regions when one investigates the problems of radiation belt formation and decay.

2.7 Effective Cutoff Rigidity in Dipole Approximation

As pointed out in Section 2.4, the influence of the earth's magnetic field on primary CRs cannot strictly be characterized by the cutoff rigidity R_c , as was done in Section 2.3, but at each observing point a penumbra function f(R) must be introduced, which is equal to 0 in the forbidden region and may jump back and forth between 0 and 1 several times before settling on the value 1 in the permitted region. In some papers cited in the preceding section, the effective geomagnetic cutoff rigidity R_c was then defined by

$$\int_{R_{\rm c}}^{\infty} \mathrm{d}R = \int_{0}^{\infty} f(R) \mathrm{d}R.$$
(2.80)

However, Eq. 2.80 is a useful definition only if the primary CR spectrum D(R) = const and is recorded above the atmosphere. Let the penumbra cover the energy interval $R_{\min} - R_{\max}$, where $R < R_{\min}$ is the completely forbidden region, and $R > R_{\max}$ the completely permitted region. When recording any secondary component of type i originating from a primary spectrum D(R), the following expression for determining the effective cutoff rigidity R_{ci} is appropriate:

$$\int_{R_{\min}}^{\infty} f(R) m_i(R, h_o) D(R) dR = \int_{R_{ci}}^{\infty} m_i(R, h_o) D(R) dR,$$
 (2.81)

or (taking into account that f(R) = 1 at $R > R_{max}$)

$$\int_{R_{\min}}^{R_{\max}} f(R) m_i(R, h_0) D(R) dR = \int_{R_{ci}}^{R_{\max}} m_i(R, h_0) D(R) dR, \qquad (2.82)$$

where $m_i(R, h_o)$ is the integral multiplicity. Thus, strictly speaking, different instruments at one observing point will have different cutoff rigidities. Therefore, the customary method in which the spectrum of the variations is determined from observed amplitudes in various components at one point, on the assumption of equal cutoff rigidity for all components, is not strictly correct. More precisely, the effective geomagnetic cutoff rigidity R_{cik} for a type i detector and a type k variation of the primary spectrum $\Delta_k D(R)/D(R)$ recorded at an altitude with pressure h_o is determined by the equation

$$\int_{R_{\min}}^{R_{\max}} f(R) W_{oi}(R, h_o) \frac{\Delta_k D(R)}{D(R)} dR = \int_{R_{cik}}^{R_{\max}} W_{oi}(R, h_o) \frac{\Delta_k D(R)}{D(R)} dR.$$
 (2.83)

In the relatively small interval $R_{\min} - R_{\max}$, the coupling coefficients can be represented in the form of a power function

$$W_{\rm oi}(R,h_{\rm o}) \propto R^a, \tag{2.84}$$

where a is positive in the low-energy region and negative for large R. Similarly, the primary variation can be represented in this interval by

$$\frac{\Delta_k D(R)}{D(R)} \propto R^b. \tag{2.85}$$

The integrand on the right-hand side of Eq. 2.83 can then be written as

$$W_{\text{oi}}(R,h_{\text{o}})\frac{\Delta_{k}D(R)}{D(R)} = A \times R^{\gamma}, \qquad (2.86)$$

where $\gamma = a + b$ and A is a constant, irrelevant for further computations. The function f(R) can be represented in the form

$$f(R) = \begin{cases} 1 \text{ for } R_{2m-1} \le R \le R_{2m}, \\ 0 \text{ for } R_{2m} \le R \le R_{2m+1}, \end{cases}$$
(2.87)

where m are integers, and $1 \le m \le n$ with $R_1 = R_{\min}, R_{2n+1} = R_{\max}$. Substitution of Eq. 2.87 into Eq. 2.83 with taking into account Eq. 2.86 gives

$$\sum_{m=1}^{n} \left(R_{2m}^{\gamma+1} - R_{2m-1}^{\gamma+1} \right) = R_{\max}^{\gamma+1} - \left(R_{cik} \left(h_o \right) \right)^{\gamma+1},$$
(2.88)

Hence, for the required effective cutoff rigidity, we find

$$R_{cik}(h_{\rm o}) = \left[R_{\rm max}^{\gamma+1} - \sum_{m=1}^{n} \left(R_{2m}^{\gamma+1} - R_{2m-1}^{\gamma+1} \right) \right]^{\frac{1}{\gamma+1}}.$$
 (2.89)

Thus, for each observing point, $R_{cik}(h_o)$ is a function of γ . Figure 2.10 shows f(R) for the geomagnetic latitudes 30°, 40°, and 50° (in dipole approximation), found in Makino and Kondo (1965). This figure explains the notations used in Eqs. 2.87–2.89 for n = 2.

In Dorman and Gushchina (1967a, b) the effective cutoff rigidities were computed from Eq. 2.89 as a function of γ (obtained results are shown in Fig. 2.11).



Fig. 2.10 Penumbra function f(R) in the dipole approximation for three geomagnetic latitudes according to Makino and Kondo (1965); the bottom panel explains the notations used in Eqs. 2.7.8–2.7.10 for n = 2



Fig. 2.11 Effective cutoff rigidity as a function of $\gamma = a + b$ (From Dorman and Gushchina, 1967a, b)

From Fig. 2.11 it can be seen that, first, the effective cutoff rigidity at all latitudes decreases with decreasing γ from +3 to 8, and, second, that the largest variations of the effective cutoff rigidity are expected at latitude 30° and amount to 0.093 GV for

a variation of 1 in γ . At latitudes 40° and 50° the same change in γ shifts the effective geomagnetic cutoff rigidity by 0.0045 GV and 0.007 GV, respectively. Table 2.2 gives examples of the expected effective rigidity changes for these three geomagnetic latitudes. The values of the exponent a, for different coupling coefficients were taken from Dorman (M2004, Chapter 3).

Table 2.2 shows that even in a quiet period, a clear difference in effective geomagnetic cutoff rigidity for different recorded components exists. At latitude 30° the effective rigidity changes from 9.20 GV, for recording on low satellites, to 9.33 GV, for the neutron component at sea level, and to 9.56 GV for the hard component at sea level. Still larger changes will arise from different variations of primary CRs. For instance, the cutoff rigidity for the neutron component at sea level may be expected to vary, in a constant geomagnetic field, between 9.28 and 8.79 GV at 30° geomagnetic latitude, between 5.378 and 5.354 GV at 40°, and between 2.679 GV and 2.638 GV for observations at latitude 50°. The corresponding variations for the hard component at sea level are 9.52–8.98, 5.387–5.362, and 2.687–2.645 GV. The Table 2.2 also shows the expected variations for many other types of recording, including underground observations at small depths, for various shapes of the primary spectrum variations.

2.8 Checking of Dipole Model by Measurements of CR Equator

According to the above-considered dipole model of the geomagnetic field, the minimum of CR intensity is expected at the geomagnetic latitude where cutoff rigidity is maximal, i.e., at the geomagnetic equator. However, the first careful measurements of the latitude effect of the hard component by Johnson and Read (1937) in 1935 showed that the minimum of CR intensity at longitude 80° W lies about 5° north of the geomagnetic equator; Clay (1934) in 1933 found a shift to the north of 4° along the meridian 3° W; Compton and Turner (1937) showed that in 1936 the minimum of CR intensity along 170° W lies, to the contrary, south of the geomagnetic equator. At that time, no great significance was attached to these relatively small differences in the theory. The alternative explanation that they might be related to the distorting influence of the local temperature effect (Dorman, 1954; Maeda, 1956), could not be ruled out since no simultaneous radio sounding data were available to check the temperature of the atmosphere above the recording instrument.

A decisive answer from the latitude effect of the neutron component, which is not influenced by the atmospheric temperature, was given by Simpson (1956) by means of neutron monitors aboard expedition ships to Antarctica in 1954/55 and 1955/56. The ships passed the equator several times so that the position of the minima in the curves of the CR latitude effect could be accurately determined at different longitudes. Besides the measurements cited above (Clay, 1934; Compton and Turner, 1937; Johnson and Read, 1937), those by Simpson (1951) in 1948 at longitude 77° W (minimum 4° north of the geomagnetic equator) and by Law et al. (1949)

latitudes 30° and 40°) (According to Dorman	n and Gush	196 nchina,	67a, b)									
Type of observation						Bursts	of solar cosr	nic rays				
			b = 2				b = 4				b = 6	
		30°	40°	4,	0 ₀	30°	40°	50°	30°	0	40°	50°
On low satellites and in the stratosphere; $a = 2.5$		9.01	5.360	.2	642	8.84	5.351	2.628	8.69	6	5.342	2.616
Neutron component for $h_0 = 312 \text{ g cm}^{-2}$ (10 km); $a = 1.5$ 1.35	53; 1.1;	9.10	5.366	2	671	8.92	5.358	2.655	8.7	7	5.348	2.643
Neutron component for ho = 680 g/cm2 (mountain level) a = 1.53; 0.59; 0.59	;(9.10	5.369	4	665	8.92	5.359	2.649	8.7	7	5.351	2.636
Neutron component at sea level for $h_0 = 1000 \text{ g cm}^{-2}$; $a = 0.0$; 0.94	= 1.23;	9.12	5.372	6	666	8.95	5.362	2.652	8.7	6	5.354	2.638
Hard component for $h_0 = 312 \text{ g cm}^2$ (10 km); $a = 1.26$; 0:); 0.88	9.12	5.371	6	667	8.94	5.362	2.615	8.78	8	5.354	2.638
Hard component at sea level for ho = 1,000 g cm ⁻² ; $a = 2.06$; 1.94	1.12;	9.36	5.38	5	675	9.16	5.371	2.660	8.9	8	5.362	2.645
Hard component at sea level, underground at depth 7 m.w $a = 2.7$; 5.6	v.e.;	9.42	5.385			9.22	5.376		0.6	3	5.367	
Type of observation		Quiet period					Mo	dulation effe	cts			
		b = 0			b = 0.5			b = 1.0			b = 1.5	
	30°	40°	50°	30°	40°	50°	30°	40°	50°	30°	40°	50°
On low satellites and balloons; $a = 2.5$	9.20	5.369	2.656	9.15	5.367	2.652	9.1	5.364	2.649	9.05	5.362	2.645
Neutron component, $h_0 = 312 \text{ g cm}^{-2}$; $a = 1.53$; 1.1; 1.35	9.30	5.375	2.686	9.25	5.368	2.682	9.19	5.371	2.677	9.15	5.368	2.675
Neutron component, $h_0 = 680 \text{ g cm}^{-2}$; $a = 1.53$; 0.59 ; 0.59	9.30	5.377	2.68	9.25	5.375	2.676	9.19	5.373	2.673	9.15	5.371	2.669
Neutron component, $h_0 = 1000 \text{ g cm}^{-2}$; $a = 1.23$; 0; 0.94	9.33	5.380	2.683	9.28	5.378	2.679	9.22	5.376	2.675	9.18	5.374	2.672
Hard component, $h_0 = 312 \text{g cm}^{-2}$; $a = 1.26$; 0; 0.88	9.325	5.380	2.682	9.28	5.378	2.678	9.22	5.376	2.675	9.18	5.374	2.671
Hard component, $h_0 = 1000 \text{ g cm}^{-2}$; $a = 1.12$; 2.06; 1.94	9.56	5.389	2.690	9.52	5.387	2.687	9.47	5.385	2.683	9.41	5.382	2.679
Hard component, underground at depth 7 m.w.e.; $a = 2.7$; 5.6	9.62	5.394		9.57	5.391		9.53	5.389		9.48	5.386	

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Fig. 2.12 Comparison of the geomagnetic equator according to the dipole representation and the CR equator – drawn in geographic coordinates (According to Simpson, 1956)

along 121° E (minimum 3° south of the geomagnetic equator) were used to determine the CR equator. It turned out that the data from different authors were lying on a smooth curve (see Fig. 2.12) which shows beyond doubt that a real difference between the geomagnetic and CR equators had been discovered.

Numerous later studies of the latitude effect from ships and airplanes, for instance, Rose et al. (1956), Skorke (1956), Kodama and Miyazaki (1957), Simpson et al. (1956), Katz et al. (1958), Pomerantz et al. (1958), Storey (1959), Kopylov and Okulov (1961), and Pomerantz and Agarwal (1962), confirmed this. It was found that variation in solar activity does not change the position of the CR equator relative to the geomagnetic equator within the measuring errors of about 1° (Kodama, 1960; Pomerantz et al., 1960).

2.9 The Checking of Dipole Model by Direct Cutoff Rigidity Measurements

A further check of the dipole model came from direct measurements of the cutoff rigidity with the aid of photo-emulsion stacks in the stratosphere. Waddington (1956) concluded from measurements of primary α particles that in computations of the energy threshold the usual geomagnetic latitude should not be used, but a value which is 4–6° smaller in Europe and about 3° larger in America. Substantial differences between the measured cutoff rigidities and the values expected for a dipole field were also found by MacDonald (1957). The cutoff rigidity was also measured directly, by means of balloons and satellites in the latitude interval 45–70° by Bingham et al. (1968).

2.10 Checking of Dipole Model by Data on CR Variations

A clear difference between the CR coordinates and the geomagnetic ones is also found in studying the CR time variations. For instance, during the second phase of the solar CR burst of February 23, 1956, when the flux of solar particles was nearly isotropic, the intensity of various secondary components was studied in Section 45.5 of Dorman (M1957), and in Marsden and Wilson (1958). The ratio of the neutron intensity increases in Leeds and Chicago remained about 0.7 from 4 h till 18 h UT. The fact that this ratio is less than unity, though Leeds is at a higher geomagnetic latitude than Chicago, is again a consequence of the difference between the system of geomagnetic coordinates and the coordinate system valid for CRs. Theoretical calculation of Dorman (M1957) with the aid of the coupling coefficients showed that the flux should at equal geomagnetic latitude be 1.1-1.2 times smaller in Europe than in America for recordings of muons and about two times smaller for the neutron component, in good agreement with experiments. A similar result was obtained in Blokh et al. (1959a) from the amplitude distribution of the intensity decrease at the time of the magnetic storm of 29 August 1957. Convincing results were obtained also by Carmichael and Steljes (1960) from worldwide neutron monitor measurements during the increase of CR intensity on 17 July 1959.

2.11 Initial Interpretations of the Differences Between CR and Geomagnetic Equators

As soon as reliable data had been obtained about the difference between the CR and the geomagnetic equators, Simpson (1956) showed that these two curves can be made to roughly coincide with a relative displacement over 45° (see Fig. 2.12). He suggested that the effect might be due to distortion of the geomagnetic field at large distances by interaction of the rotating dipole of the earth with the interplanetary medium. This hypothesis was developed by Maeda (1958), who showed that the oblique dipole, rotating together with the earth, should displace the effective equator to the west of the geomagnetic over an angle which depends on the dimensions of the geomagnetic cavity. He also pointed out that the electromagnetic interaction with the interplanetary medium should also lead to a small retardation of the rotation of the earth. Similar ideas were developed by Beiser (1958) and Ingraham (1959).

However, many other investigators advanced weighty arguments to attribute the effect to the particular distribution of the magnetic field near the earth's surface rather than to a distortion of the field at large distances. Computations by Jory (1956) showed that the geomagnetic fields of a quadrupled character found from the magnetic survey of 1945, could actually have an essential influence on CR intensity. In further works (Vallarta et al., 1958; Kellogg and Schwartz, 1959; Kellogg, 1960), computations for non-dipole fields were extended and refined by bringing in terms up to the sixth order. All these studies make it clear that the distribution of the

magnetic field close to the earth's surface has a strong influence on the particle trajectories and on the values of cutoff rigidity, for the field, due to the high-order spherical harmonics, drops rapidly with height. The same point is illustrated by the good agreement between the CR equator and the curve of zero dip (dip equator) and by Sandström's analysis (1959) of neutron flux measured aboard an airplane.

The most direct method for finding trajectories and cutoff rigidities in the given geomagnetic field – numerical integration of the equations of motion of a negative particle emitted from the surface of the earth – involves a huge amount of computation. Therefore many authors have tried to solve this problem either by simplifying Störmer's theory, so that the cutoff rigidity can be determined without determining the orbits, or by generalizing this theory so as to take the influence of the higher harmonics into account, if only approximately. Thus, Baxter and Kelsall (1962) have computed accurate cutoff rigidities for protons in a dipole magnetic field, taking into account the dependence on zenith and azimuth angles of incidence, geomagnetic latitude, etc. The following approximation was found by Sauer and Ray (1963): they neglected the influence of the higher harmonics at large distances and showed that, at low latitudes, the cutoff rigidity remains approximately constant for a shift along a magnetic force line. Sauer (1963) computed cutoff rigidities of vertically incident particles for CR stations with geomagnetic latitudes $|\lambda| \ge 45^{\circ}$. Again, for distances larger than a certain value r, a dipole field was used. Störmer's solution being applied, but at smaller distances, six terms of the development of the geomagnetic field in spherical harmonics were taken into account and the equation of motion of the particles was integrated numerically.

2.12 Impact Zones, Asymptotic Directions, and Acceptance Cones in the Dipole Magnetic Field

Solution of this problem requires a large body of numerical computations; therefore a review of the available information will be useful. The principal features can already be seen in the dipole approximation, which suffices in some practical applications. The literature over several decennia contains many relevant computations. After Störmer's first numerical calculations of trajectories in a dipole field (see the review in Störmer, M1955), Boguslavsky (M1929) studied many particular cases of trajectories. Lanza (1965) gave asymptotic directions in the form of nomograms. Model experiments of Brunberg (1953, 1956), Brunberg and Dattner (1953) on the asymptotic angles of trajectories of charged particles in the field of a magnetic dipole have been widely used. Using further orbit computations by Dwight (1950), Schlüter (1951), and Malmfors (1945), Firor (1954) computed the impact zones for particles reaching the earth in the direction from the sun. Four hundred new trajectories were computed by Lüst et al. (1955).

Jory (1956) published computations of 663 trajectories of particles with rigidities in the interval from 1 GV to 10 GV, emitted by the sun. Orbits are considered of particles arriving at the boundary of the atmosphere along the vertical and under

angles of 16° and 32° north, east, south, and west of the vertical. On the assumption that the rigidity spectrum is flat in the interval 1–10 GV, i.e.,

$$D_S(R) = \begin{cases} \text{const, for } 1\,\text{GV} \le R \le 10\,\text{GV}, \\ 0, & \text{for } R < 1\,\text{GV}, R > 10\,\text{GV}, \end{cases}$$
(2.90)

and that the particle source has a rectangular shape (solid angle $\pm 5^\circ$ in latitude and $\pm 10^{\circ}$ in longitude), the impact zones of the particles on the earth are found at various geomagnetic latitudes (at intervals of 10°), and also the particle intensity in these zones. He finds that at intermediate latitudes the chief impact zone must lie at about 3 h, and at high latitudes at about 9 h local time. Lüst (1957) extended this work with the examination of 1,500 orbits of particles coming from a region near the sun and determined the regions on the earth where these particles may arrive. These computations were performed for various positions of the source: in the plane of the geomagnetic equator and shifted by $\pm 20^{\circ}$. It turned out that there should be clearly marked impact zones on earth, depending little on the solid angle of the source. At low latitudes, only the 3 h zone occurs, at high latitudes the 9 h zone occurs. The impact zone is said to be at 3 h if the particles arrive at the points on earth for which the local solar time at the moment when the flux was ejected was 3 h. Particles arrive in each zone, in the rigidity interval characteristic for this zone. The position of the zones and the intensity of the particle flux in each of them depend strongly on the position of the source; in some cases the magnetic field of the earth causes the particle flux to be focused, particularly at high latitudes. The latter result agrees with results of computations by Aström (1956). An experimental check of the width of the zones can best be made between latitudes 60° and 70° where the background radiation consists of particles with rigidity less than 1 GV, which do not reach the earth's surface.

In a further article, Lüst (1958), assuming that the source of solar CR has an extension of $\pm 15^{\circ}$ in latitude and $\pm 10^{\circ}$ in longitude, and that it has a differential rigidity spectrum $\propto R^{-6}$ in the interval 1 GV < R < 30 GV computes the expected total solar CR intensity at the top of the terrestrial atmosphere as a function of local time and geomagnetic latitude for a source position at geomagnetic latitude 20° , as it was during the greatest FEP event on February 23, 1956. Results are shown in Fig. 2.13.

The sun may also emit protons with a very small kinetic energy down to 0.010 GeV (rigidity 0.14 GV), or even 0.001 GeV (rigidity 0.045 GV). Therefore, Sakurai (1960) computed the impact zones for particles with rigidity 0.03, 0.1 and 0.6 GV. Figure 2.14 shows the relation between the geomagnetic latitude λ of impact and the latitude of the source λ_{∞} , and Fig. 2.15 shows the relation between λ_{∞} and the angle of escape φ_{∞} ; with the aid of these results, the impact zones can be found for various assumptions about the angular dimensions and the position of the source relative to the geomagnetic equator.

The assembly of all asymptotic directions forms the acceptance cone. Therefore, the counting rate of any CR detector depends on the way in which the geomagnetic field transforms the infinitely small elements of solid angle forming the receiving



Fig. 2.13 Computed counting rates at the top of the atmosphere on the assumption that the sun is in the position it had been on February 23, 1956 (According to Lüst, 1958)

cone of the detector. Boström (1964) shows that for any latitude of the detector, the ratio M of the receiving solid angle and the solid angle outside the geomagnetic field M > 1, and for some rigidities $M \gg 1$. Thus the geomagnetic field exerts a focusing action on CRs, in particular for detectors of soft particles at high-latitude stations


Fig. 2.14 Graphs for determining the impact zones for particles with different rigidity from 0.03 GV up to 10 GV for the northern hemisphere (for the southern hemisphere results will be symmetric); relations between λ and λ_{∞} (According to Sakurai, 1960)



Fig. 2.15 The same as in Fig. 2.14, but for relations between λ_{∞} and φ_{∞} (According to Sakurai, 1960)

(see in more detail Section 2.14). For determining the direction of an anisotropic source, high-latitude stations are most suitable; detectors at low-latitude stations are sensitive to sources near the equatorial plane only.

In order to avoid cumbersome numerical computations of orbits for low-energy particles, Webber (1963) based his analysis on the properties of motion in Alfvén regime and on analysis of the families of orbits computed by Störmer (see Chapter 3, this volume for more detail on Alfvén and Störmer regimes). By this method asymptotic directions are found for a wide range of geomagnetic latitudes, without numerical integration. Webber (1963) also generalized this method for the case of a non-dipole field and found the asymptotic directions for a number of actual stations.

Kudryavchenko (1962) computed the average effective angles ψ (the angle of trajectory shift in the plane of the equator) and φ (the angle between the effective direction of incidence of the particles and the plane of the geomagnetic equator) for cubic telescopes and neutron monitors at different geomagnetic latitudes (analogous to the computations described in Section 15.2 in Dorman, M1957), and the corresponding variation of the effective angles during Forbush effects. Analogous computations may be found in papers by Fenton et al. (1959) and Fedchenko (1961). The coupling coefficients in these papers were taken from Figs. 30 and 242 in Dorman (M1957), and the angles $\psi(R)$ and $\phi(R)$ for various zenith and azimuth angles from the work of Brunberg and Dattner (1953). For obliquely incident particles, the above-mentioned exponential factor has also been included. The effective angles ψ and ϕ , computed in dipole approximation by Lapointe and Rose (1961), and angular width of the effective sensitivity cones $\Delta \psi$ and $\Delta \psi$ are given in Table 2.3 as a function of the geomagnetic latitude of the neutron monitor. Table 2.4 shows the geographic latitude and longitude of the asymptotic directions of the highest sensitivity for neutron monitors at 22 stations.

Geomagnetic latitude	ψ	φ	Δψ	$\Delta \phi$	Geomagnetic latitude	Ψ	φ	$\Delta \psi$	$\Delta \varphi$
$\overline{0^{\circ}}$	77°	0°	38°	8°	50°	55°	-1°	22°	16°
5°	81°	-1°	44°	8°	55°	43°	9°	13°	17°
10°	83°	-2°	48°	9°	60°	36°	21°	10°	14°
15°	79°	-2°	40°	11°	65°	32°	31°	10°	12°
20°	72°	-3°	33°	13°	70°	28°	44°	13°	9°
25°	72°	-3°	31°	15°	75°	27°	57°	17°	8°
30°	80°	-3°	41°	16°	80°	25°	67°	22°	7°
35°	79°	-5°	37°	16°	85°		79°		
40°	75°	-5°	32°	17°	90°		90°		
45°	69°	-5°	30°	17°					

Table 2.3 Computed values of effective angles ψ and ϕ , and effective sensitivity cones $\Delta \psi$ and $\Delta \phi$ for neutron monitors as functions of geomagnetic latitude (According to Lapointe and Rose, 1961)

Station	Direction ser	of the highest sitivity	Station	Direction of the highest sensitivity		
	Latitude	Longitude		Latitude	Longitude	
Berkeley	16° S	$60^{\circ} \mathrm{W}$	Ottawa	3° N	$40^{\circ} \mathrm{W}$	
Mt. Washington	2° N	38° W	Pic-du-Midi	5° N	78° E	
Mt. Wellington	4° S	155° W	Resolute	64° N	$97^{\circ} \mathrm{W}$	
Deep River	6° N	$40^{\circ} \mathrm{W}$	Rome	6° N	95° E	
Climax	$14^{\circ} \mathrm{S}$	$50^{\circ} \mathrm{W}$	Sydney	0°	$130^{\circ} \mathrm{W}$	
College	28° N	132° W	Thule	74–84° N		
Leeds	$20^{\circ} \mathrm{N}$	53° E	Uppsala	27° N	72° E	
Lincoln	$10^{\circ} \mathrm{S}$	$40^{\circ} \mathrm{W}$	Herstmonceux	14° N	60° E	
Mawson	44° S	$70^{\circ} \mathrm{E}$	Zugspitze	$7^{\circ} N$	85° E	
Munich	8° N	82° E	Churchill	31° N	$75^{\circ} \mathrm{W}$	
Mt. Norikura	5° S	$151^{\circ}\mathrm{W}$	Chicago	0°	$45^{\circ}\mathrm{W}$	

 Table 2.4 Geographic latitude and longitude of the asymptotic directions of the highest sensitivity for neutron monitors in dipole approximation of geomagnetic field (According to Lapointe and Rose, 1961)

2.13 Seasonal and Daily Variation of the Position of Impact Zones in Dipole Approximation

The position of the source of solar CR changes relative to the geomagnetic equator during the day and during the year according to the change in the relative position of the sun. The character of changes directly follows from Figs. 2.14 and 2.15. The expected daily and season variations of the position of the impact zones, can also be found from the results obtained by Jory (1956b), Lüst (1957), Kelsall (1961), and other authors. Particularly, in Kelsall (1961), 4,000 numerical orbit integrations were performed for protons with energies from 0.05 GeV to 50 GeV, assuming different orientations of the incident solar particle stream with respect to the dipole axis. Two facts, which are not new but were overlooked in earlier work, emerged from this study: (1) the relative number of impacts in the northern and southern hemispheres strongly depends on the season; and (2) for certain seasonal conditions there is a class of orbits which might be called "quasi-trapped", resembling the orbits of trapped particles predicted by Störmer. Injection into trapped (periodic) orbits from these quasi-trapped particles may contribute to the intensity of the radiation belts. This may be one of the causes of time variations of the radiation trapped in the radiation belts.

Kaminer (1960), on the basis of published data on solar CR particle trajectories in the approximation of the dipole magnetic field, prepared special graphics for quickly determining longitude and latitude of 9 h and 4 h impact zones on earth in dependence of UT (from 0 to 24 h) and of the position of the sun relative to the earth's geographical equator (from -23° to $+23^{\circ}$). It was supposed that the emitted spectrum of solar energetic particles lasted from 1 to 10 GeV, the latitude



Fig. 2.16 Graphics for quickly determining the latitude of the 9 h impact zone in dependence of UT (from 0 to 24 h) and of the position of the sun relative to the earth's geographical equator (from -23° to $+23^{\circ}$, numbers near curves) (From Kaminer, 1960)

angle dimension of source is equal to $\pm 15^{\circ}$, and in the longitude direction it may be described by the δ -function. The obtained results are shown in Figs. 2.16–2.19.

On the basis of the graphics presented in Figs. 2.16–2.19, it is very easy to determine the position of the 9 h and 4 h impact zones for any CR station. As an example, Fig. 2.20 shows the seasonal changes of impact zones' positions for several stations in the former USSR: Apatity, Yakutsk, Moscow, Irkutsk, and Tbilisi.

Let us note that with the development of solar CR event in time, the flux became more isotropic, so these impact zones really only exist at the initial stage of the event (see Dorman and Miroshnichenko, M1968; Dorman, M1978, Miroshnichenko, M2001).

2.14 Asymptotic Accepted Cones and Expected Counting Rates of CR Detectors; Focusing Properties of Geomagnetic Field

The counting rates of a CR detector of type i will be determined by the following expression:

$$N_i(h_o) = \int_{\omega} \mathrm{d}\omega \int_a \mathrm{d}a \int_R D(R,\xi,\chi) m_i(R,\xi,\chi,h_o) \,\mathrm{d}R, \qquad (2.91)$$

where $D(R, \xi, \chi)$ is the intensity of CR incident on the boundary of the atmosphere at zenith angle ξ and azimuthally angle χ , $m_i(R, \xi, \chi, h_o)$ is the integral multiplicity. Integration in Eq. 2.91 takes over the surface *a* and over the space angle ω on



Fig. 2.17 Graphics for quickly determining the longitude of the 9 h impact zone in dependence of UT (from 0 to 24 h) and of the position of the sun relative to the earth's geographical equator (from -23° to $+23^{\circ}$, numbers near curves) (From Kaminer, 1960)

the boundary of the atmosphere which corresponds to the detector on the level h_0 . According to the Liouville theorem, in the static magnetic field along the particle trajectory the intensity remains constant, i.e.,

$$D(R,\xi,\chi) = D(R,\Phi,\Lambda), \qquad (2.92)$$

where $D(R, \Phi, \Lambda)$ is the flux of primary CR out of the geomagnetic field in dependence of the asymptotic geomagnetic longitude Φ and asymptotic geomagnetic latitude Λ . Equation 2.92 is valid only along the trajectory, therefore, Φ and Λ are functions of ξ, χ , and *R*:

$$\Phi = \Phi(\xi, \chi, R); \quad \Lambda = \Lambda(\xi, \chi, R).$$
(2.93)



Fig. 2.18 Graphics for quickly determining the longitude of the 4 h impact zone in dependence of UT (from 0 to 24 h) and of the position of the sun relative to the earth's geographical equator (from -23° to $+23^{\circ}$, numbers near curves) (From Kaminer, 1960)

According to Swann (1933), Eq. 2.92 can be written in the following form:

$$\mathrm{d}\Omega\mathrm{d}A_h = \mathrm{d}\omega_h\mathrm{d}a,\tag{2.94}$$

where $d\Omega$ and dA_h are elements of space angle and surface out of the geomagnetic field, and $d\omega_h$ and da are the same values but at the boundary of the atmosphere. The introduction of index h = 1, 2, 3, ... is caused by the fact that there are no simple connections between the asymptotical direction determined by angles Φ and Λ with direction at the boundary of the atmosphere determined by zenith angle ξ and azimuthally angle χ . Different values ξ and χ at definite rigidity R can correspond to the same direction Φ , Λ , but at different positions in space dA_h . Correspondingly, for definite asymptotical direction $d\Omega$ but at different elements of surface dA_h out of the geomagnetic field, will correspond on the boundary of the atmosphere with one element of surface da, but with different elements of space angle $d\omega_h$. To characterize the change of space angle at the crossing of the geomagnetic field by the flux of charged energetic particles, Brunberg (1958) introduced a coefficient for amplifying of the space angle

$$M_h(\Phi, \Lambda, R) = \mathrm{d}\omega_h/\mathrm{d}\Omega. \tag{2.95}$$



Fig. 2.19 Graphics for quickly determining the latitude of the 4 h impact zone in dependence of UT (from 0 to 24 h) and of the position of the sun relative to the earth's geographical equator (from -23° to $+23^{\circ}$, numbers near curves) (From Kaminer, 1960)

On the basis of Eqs. 2.91–2.95, the expected counting rate of the detector will be

$$N_{i}(h_{o}) = \int_{\Omega} d\Omega \int_{a} da \int_{R} D(R, \Phi, \Lambda) \sum_{h} M_{h}(R, \Phi, \Lambda) m_{i}(R, \Phi, \Lambda, h_{o}) dR, \quad (2.96)$$

where summation takes over all elements of space angle $d\omega_h$ which correspond to the same element of space angle $d\Omega$ out of the geomagnetic field.

For practical use of Eq. 2.96, it is convenient to introduce differential coefficients of sensitivity of the CR detector as follows. Let us divide the full space angle Ω out of the geomagnetic field over many small elements $\Delta\Omega_{jk}$ displaced in a direction characterized by asymptotical longitude Φ_j and latitude Λ_k , and rigidity to divide over many small elements ΔR_l . Let us choose the elements so small that inside each of them, primary CR flux D_{jkl} can be considered as homogeneous and constant. Now the counting rate of the CR detector will be expressed as

$$N_i(h_{\rm o}) = \sum_j \sum_k \sum_l D_{jkl} S_{ijkl} \Delta \Omega_{jk} \Delta R_l, \qquad (2.97)$$



Fig. 2.20 Seasonal change of position of the 9 h and 4 h impact zones for CR stations Apatity, Yakutsk, Moscow, Irkutsk, and Tbilisi (According to Kaminer, 1960)

where

$$S_{ijkl} = a \sum_{h} m_{ijklh} M_{jklh} = a \sum_{h} m_{ijklh} \frac{\Delta \omega_{jkh}}{\Delta \Omega_{jk}}.$$
 (2.98)

The focusing properties of the dipole geomagnetic field were investigated in detail by Boström (1964). As an example, in Fig. 2.21 values of coefficient of amplifying M are shown for vertical incident particles at geomagnetic latitudes 0° , 20° , 45° , and 74° .

From Fig. 2.21 it can be seen that for a large interval of rigidities, the coefficient of amplifying M > 1, i.e., the dipole geomagnetic field really has focusing properties; only in small regions near the cutoff rigidity M < 1, and in these cases the geomagnetic field is defocusing. For several rigidities $M \rightarrow \infty$ and the focusing action of the geomagnetic field became especially great. With an increase of geomagnetic latitude, the focusing action of the geomagnetic field increases sufficiently (this is in agreement with the results of Aström, 1956). Therefore, the CR detectors on high latitudes will have a sufficiently larger resolution than CR detectors on low



Fig. 2.21 Focusing properties of the dipole geomagnetic field for vertical incident particles at geomagnetic latitudes 0° , 20° , 45° , and 74° (According to Boström, 1964)



Fig. 2.22 Asymptotic accepted cones in the field of the geomagnetic dipole for CR particles arriving from the vertical direction at the geomagnetic latitudes 0° , 20° , and 45° ; numbers show particle rigidity in GV (According to Boström, 1964)

latitudes. Figure 2.21 also shows that at all latitudes with a large increase of *R*, the focusing or defocusing properties of the geomagnetic field dissipated $(M \rightarrow 1)$.

Figure 2.22 shows the asymptotic accepted cones in the field of the geomagnetic dipole for CR particles that arrived from the vertical direction at latitudes 0° , 20° , and 45° , and in Fig. 2.23 at geomagnetic latitude 74° .

In Figs. 2.22 and 2.23 the change of the form of circle element of space angle during energetic charged particle bunch crossing of the geomagnetic field are also shown; only at high rigidity (100 GV) there is no change (coefficient of amplifying M = 1). On low latitudes (Fig. 2.22, panels for $\lambda = 0^{\circ}$ and $\lambda = 20^{\circ}$) asymptotic directions are in the region near the equatorial plane. With a decreasing of particle rigidity, the elements of the space angle become more and more drawn out and for corresponding rigidities $M \rightarrow \infty$, the width of elements $\rightarrow 0$. For low and middle latitude stations (see Fig. 2.22), the asymptotic directions are displaced in the broad interval of longitudes. But for high-latitude stations (Fig. 2.23) asymptotic directions are displaced in the narrow interval of longitudes and with decreasing particle



Fig. 2.23 The same as in Fig. 2.22, but for geomagnetic latitude 74°; numbers show particle rigidity in GV (According to Boström, 1964)

rigidity they shift toward the equatorial plane. With decreasing rigidities the dimension of the elements of the space angle becomes smaller, and at certain rigidities (10.5, 4.8, 3.2, and 2.3 GV, for which $M \rightarrow \infty$ according to Fig. 2.21), the dimension of elements $\rightarrow 0$.

From a comparison of Fig. 2.23 with Fig. 2.22, it also follows that at high latitudes the decreasing of the dimension of the elements of the space angle with a decreasing of particle rigidity occurs much more quickly than at low and middle latitudes. Let us note that the described peculiarities of the asymptotic directions formatted the basis of Bieber and Evenson's (1995) concept of using high-latitude CR stations for the Project "The Spaceship Earth" (see details in Dorman, M2004, Chapter 4, Section 4.4.14).

Chapter 3 Cosmic Rays in the Real Geomagnetic Field

3.1 Inner and Outer Sources of the Real Geomagnetic Field; Changing in Time

The main part of the geomagnetic field is produced by sources inside the earth: most probably there are electrical currents in the rotated liquid metallic nucleus of the earth supported by convective hydromagnetic flows (see, e.g., Braginsky, 1964a, b). As discussed in Chapter 2 (Sections 2.1–2.7 and 2.12–2.14), in the first approximation, this field can be considered as the field of magnetic dipole displaced near the center of the earth. However, as was shown in the same chapter, (Sections 2.6–2.11), the dipole presentation is not enough for describing CR equator, CR time variations, and planetary distribution of cutoff rigidities.

Outer sources of the geomagnetic field are produced by three systems of electrical currents: ionosphere currents, ring current, and currents on the boundary of the magnetosphere (see Chapter 6 for details). The influence of the magnetic field of ionosphere currents on CR particles' moving is usually considered as negligible. The western directed ring current in the earth's magnetosphere is the most important for the geomagnetic field changing in time as well as for the influence on CR particles moving in the magnetosphere (this influence will be considered in detail in Chapter 7). The ring current is caused by charged particles trapped in the radiation belts: beside the rotation of these particles around the magnetic force lines and moving along the force lines between mirror points in the north and south, they also have a drift in the direction perpendicular to the magnetic field lines and to the gradient of the magnetic field (positive particles drifted in the western direction and negative – in the eastern direction, so the total electrical current will be in the western direction). The distribution of this western ring current depends on the distribution of the charged energetic particles, and their velocities and pitch angles (see for more detail in Dessler and Parker, 1959; Akasofu and Chapman, 1961, and in Chapter 6).

The vector of geomagnetic field is characterized in the Descartes system of coordinates (introduced by French philosopher and mathematician Rene Descartes, 1596–1650), by components north (usually denotes as X), east (Y), and vertical (Z);

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in the cylindrical system by horizontal component H, vertical Z, and declination D; in the spherical system by the module of magnetic force H, declination D, and inclination I. These components of geomagnetic field changed in time: short-term variations are mostly caused by outer sources in the magnetosphere and long-term variations – mostly by interior sources inside the earth.

3.2 Presentation of the Real Geomagnetic Field by Series of Spherical Harmonics; Gauss Coefficients

In the 19th century, the famous German scientist Carl Gauss (1777–1855) developed a theory that analytically presented the real geomagnetic field on the earth's surface and in space as a sum of spherical harmonics. The basis of Gauss theory was the supposition that all main sources of the geomagnetic field are inside the earth. In this case, there will be no electrical currents in the outer-space of the earth. This means that

$$rot\mathbf{H} = 0. \tag{3.1}$$

Therefore, the vector of geomagnetic field H on the earth's surface and out of the earth can be presented as a gradient of some scalar function $U(\mathbf{r})$ because rotgrad $U(\mathbf{r}) \equiv 0$. So we can suppose that

$$\mathbf{H} = -\operatorname{grad} U\left(\mathbf{r}\right),\tag{3.2}$$

and because divH = 0, we obtain the Laplace equation for scalar potential of geomagnetic field

$$\operatorname{div}\left(\operatorname{grad} U\left(\mathbf{r}\right)\right) = \nabla^{2} U\left(\mathbf{r}\right) = 0. \tag{3.3}$$

In the spherical system of coordinates Eq. 3.3 will be

$$r^{2}\frac{\partial^{2}U}{\partial r^{2}} + 2r\frac{\partial U}{\partial r} + \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial U}{\partial\theta}\right) + \frac{1}{\sin^{2}\theta}\frac{\partial^{2}U}{\partial\varphi^{2}} = 0, \quad (3.4)$$

where r, θ, φ are the spherical coordinates: radius–vector, addition to the geographic latitude $\lambda(\theta = 90^\circ - \lambda)$, and geographic longitude. The solution of Eq. 3.4 can be found in the form

$$U(r,\theta,\varphi) = f(r)\Phi(\theta,\varphi).$$
(3.5)

Let us substitute Eq. 3.5 into Eq. 3.4 and, after division of variables, we obtain

$$\begin{cases} r^{2} \frac{d^{2} f(r)}{dr^{2}} + 2r \frac{df(r)}{dr} - n^{2} f(r) = 0, \\ \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial \Phi(\theta, \varphi)}{\partial \theta} \right) + \frac{1}{\sin^{2} \theta} \frac{\partial^{2} \Phi(\theta, \varphi)}{\partial \varphi^{2}} + n^{2} \Phi(\theta, \varphi) = 0, \end{cases}$$
(3.6)

where n^2 is the constant of the division of variables.

The first equation in the system of Eq. 3.6 is the well-known Euler equation with the solution

$$f(r) = A_n r^n + B_n r^{-(n+1)}, \qquad (3.7)$$

where A_n and B_n are arbitrary constants of integration and n is any positive integer value.

The second equation in the system of Eq. 3.6 can be also solved by the method of variables division:

$$\Phi(\theta, \varphi) = \xi(\theta) \psi(\varphi). \tag{3.8}$$

By substituting Eq. 3.8 into the second equation of Eq. 3.6, we obtain

$$\begin{cases} \frac{d^2\psi(\varphi)}{d\varphi^2} + m^2\psi(\varphi) = 0, \\ \left(\frac{d}{d\theta}\left(\sin\theta\frac{d\xi(\theta)}{d\theta}\right) + \left(n(n+1)\sin^2\theta - \frac{m^2}{\sin\theta}\right)\xi(\theta) = 0, \end{cases}$$
(3.9)

where m^2 is the constant of the division of variables. The solution of the first equation of the Eq. 3.9 will be the simple harmonic function

$$\psi(\varphi) = \alpha_n^m \sin m\varphi + \beta_n^m \cos m\varphi, \qquad (3.10)$$

and the solution of the second equation of the Eq. 3.9 will be Légandre polynomials

$$\xi\left(\theta\right) = P_n^m\left(\cos\theta\right). \tag{3.11}$$

Substituting into Eq. 3.5 f(r) determined by Eq. 3.7 and $\Phi(\theta, \phi)$ determined by Eqs. 3.8, 3.10, and 3.11, we obtain the following partial solution of the Laplace equation 3.4:

$$U(r,\theta,\varphi) = \left(A_n r^n + \frac{B_n}{r^{n+1}}\right) \left(\alpha_n^m \sin m\varphi + \beta_n^m \cos m\varphi\right) P_n^m(\cos\theta).$$
(3.12)

Because the Laplace equation 3.4 is linear, the general solution can be presented as a sum of partial solutions in two forms:

$$U_1(r,\theta,\varphi) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} r^n \left(c_n^m \sin m\varphi + d_n^m \cos m\varphi \right) P_n^m \left(\cos \theta \right), \qquad (3.13)$$

$$U_{2}(r,\theta,\varphi) = \sum_{n=0}^{\infty} \sum_{m=0}^{n} r^{-(n+1)} \left(a_{n}^{m} \sin m\varphi + b_{n}^{m} \cos m\varphi \right) P_{n}^{m} \left(\cos \theta \right), \qquad (3.14)$$

where

$$a_n^m = B_n \alpha_n^m, \quad b_n^m = B_n \beta_n^m, \quad c_n^m = A_n \alpha_n^m, \quad d_n^m = A_n \beta_n^m.$$
(3.15)

For analyzing the magnetic field out of the earth which is caused by interior sources inside the earth, it is necessary to satisfy the boundary condition on infinity where the magnetic field must equal zero, i.e., we need to choose the solution described by Eq. 3.14. Contrarily, for analyzing the magnetic field inside the outer sources, it is necessary to satisfy the condition at the center of the coordinates that the magnetic field must be finite, i.e., we need to choose the solution described by Eq. 3.13. The first members in Eqs. 3.13 and 3.14 describe the magnetic field of the magnetic monopole, but really in any body, the sum of magnetic charges is equal to zero. This means that in the above-mentioned equations, the summation starts from n = 1. Usually, instead of coefficients a_n^m and b_n^m we use the coefficients g_n^m and h_n^m determined by the expressions

$$a_n^m = r_E^{n+2} g_n^m, \quad b_n^m = r_E^{n+2} h_n^m,$$
 (3.16)

where r_E is the radius of the earth. In this case, for inside sources of the geomagnetic field out of the earth, we obtain

$$U_2(r,\theta,\varphi) = r_{\rm E} \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{r_{\rm E}}{r}\right)^{n+1} \left(g_n^m \sin m\varphi + h_n^m \cos m\varphi\right) P_n^m(\cos\theta) \,. \tag{3.17}$$

Now by using Eq. 3.2, it is easy to determine the three components of the vector of geomagnetic field. The north (X), east (Y), and vertical (Z) components will be

$$X(r,\theta,\varphi) = -\frac{\partial U_2}{r\partial\theta} = -\sum_{n=1}^{\infty} \left(\frac{r_{\rm E}}{r}\right)^{n+2} \sum_{m=0}^{n} \left(g_n^m \cos m\varphi + h_n^m \sin m\varphi\right) \frac{\mathrm{d}P_n^m(\cos\theta)}{\mathrm{d}\theta},\tag{3.18}$$

$$Y(r,\theta,\varphi) = -\frac{\partial U_2}{r\sin\theta\partial\varphi}$$

= $\sum_{n=1}^{\infty} \left(\frac{r_E}{r}\right)^{n+2} \sum_{m=0}^{n} (mg_n^m \sin m\varphi - mh_n^m \cos m\varphi) \frac{P_n^m(\cos\theta)}{\sin\theta},$ (3.19)
 $Z(r,\theta,\varphi) = -\frac{\partial U_2}{2}$

$$(r,\theta,\varphi) = -\frac{\partial U_2}{\partial r}$$

= $\sum_{n=1}^{\infty} \left(\frac{r_E}{r}\right)^{n+2} (n+1) \sum_{m=0}^{n} (g_n^m \cos m\varphi + h_n^m \sin m\varphi) P_n^m (\cos \theta).$ (3.20)

When using Eqs. 3.18–3.20, it usually means that n_{max} is finite; the total number of coefficients g_n^m and h_n^m will be $n_{\text{max}} (n_{\text{max}} + 2)$, so at $n_{\text{max}} = 6$ and 8, the total number of Gauss coefficients will be, correspondingly, 48 and 80. For the presentation of a geomagnetic field caused by outer sources instead of coefficients c_n^m and d_n^m in Eq. 3.13, let us introduce the coefficients j_n^m and k_n^m determined by the expressions

$$c_n^m = r_E^{-(n-1)} j_n^m, \quad d_n^m = r_E^{-(n-1)} k_n^m.$$
 (3.21)

In this case, the expression for scalar potential from outer sources will be

$$U_{1}(r,\theta,\phi) = r_{\rm E} \sum_{n=1}^{\infty} \frac{r^{n}}{r_{\rm E}^{n-1}} \sum_{m=0}^{n} (j_{n}^{m} \cos m\phi + k_{n}^{m} \sin m\phi) P_{n}^{m}(\cos\theta).$$
(3.22)

From Eq. 3.22, on the basis of Eq. 3.2, it can be very easy to obtain the three components of the geomagnetic field inside of outer sources (in analogy with Eqs. 3.18– 3.20). By the summing the components of the magnetic field produced by inner and outer sources, we obtain

$$X(r,\theta,\varphi) = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(l_n^m \cos m\varphi + q_n^m \sin m\varphi \right) \frac{\mathrm{d}P_n^m(\cos\theta)}{\mathrm{d}\theta}, \tag{3.23}$$

$$Y(r,\theta,\varphi) = \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(l_n^m \sin m\varphi - q_n^m \cos m\varphi \right) \frac{m P_n^m(\cos \theta)}{\sin \theta},$$
(3.24)

$$Z(r,\theta,\varphi) = \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(l_n^{\prime m} \cos m\varphi + q_n^{\prime m} \sin m\varphi \right) P_n^m(\cos \theta), \qquad (3.25)$$

where

$$l_n^m = g_n^m + j_n^m, \quad q_n^m = h_n^m + k_n^m, \quad l_n^m = (n+1) g_n^m - n j_n^m,$$

$$q_n^{\prime m} = (n+1) h_n^m - n k_n^m.$$
 (3.26)

3.3 Relative Role of Spherical Harmonics in the Formation of the Geomagnetic Field from Internal Sources

The first spherical harmonic in Eq. 3.17 (n = 1) corresponds to the field of the magnetic dipole, the second harmonic (n = 2) to the field of the quadruple, the third harmonic (n = 3) to field of octuple, and so on. The relative role of different spherical harmonics in the formation of a real geomagnetic field from internal sources were calculated by Quenby and Webber (1959). They used Gauss coefficients g_n^m and h_n^m obtained by Finch and Leaton (1957) on the basis of spherical harmonic analysis of the magnetic maps of the epoch 1955.0. The scalar potential of the geomagnetic field from internal sources, according to Eq. 3.17, can be presented as

$$U_2(r,\theta,\varphi) = \sum_{n=1}^{\infty} U_{2n}(r,\theta,\varphi), \qquad (3.27)$$

where

$$U_{2n}(r,\theta,\varphi) = r_E \left(\frac{r_E}{r}\right)^{n+1} \sum_{m=0}^n \left(g_n^m \sin m\varphi + h_n^m \cos m\varphi\right) P_n^m(\cos\theta).$$
(3.28)

For the square of $U_{2n}(r, \theta, \varphi)$ averaged over the spherical surface on some distance $r \ge r_{\rm E}$, we obtain

$$|U_{2n}(r)|^{2} = \frac{r_{\rm E}^{2}}{2n+1} \left(\frac{r_{\rm E}}{r}\right)^{2(n+1)} \sum_{m=0}^{n} \left((g_{n}^{m})^{2} + (h_{n}^{m})^{2}\right).$$
(3.29)

Distance from the center		Order	of har	Sum of harmonics 2–6		
of the earth, $r_{\rm E}$	2	3	4	5	6	-
1.0	10.4	5.9	2.8	0.9	0.4	20.4
1.2	8.7	4.1	1.6	0.4	0.2	15.0
1.5	6.8	2.6	0.8	0.2	0.1	10.5
2.0	5.2	1.5	0.3	0.1	< 0.1	7.0
3.0	3.5	0.7	0.1	< 0.1	< 0.1	4.2

Table 3.1 The relative importance of the spherical harmonics, in percentage of the first harmonic

The role of each spherical harmonic will be determined by the value $|U_{2n}(r)|$ that can be found as the root square of Eq. 3.29. The results are shown in Table 3.1.

As can be seen from Table 3.1, all highest harmonics gave only 20.4% near the earth's surface from the first, dipole harmonic. With an increase in the distance from the center of the earth, the role of highest harmonics decreases abruptly: at distance 1.5 $r_{\rm E}$ their role became 10%, at 3.0 $r_{\rm E}$ -4.2%.

3.4 Analytical Methods of Trajectory Calculations in the Real Geomagnetic Field

3.4.1 General Equation

If the Gauss coefficients for some epoch are known, the potential of geomagnetic field $U(r, \theta, \varphi)$ can be determined in any point; this means that the vector of the magnetic field force is also known. The equation of a moving particle with the rest mass m_o , charge Ze, and velocity v(|v| = v is constant in the non-variable magnetic field) will be

$$\frac{\mathrm{d}^2 \mathbf{r}}{\mathrm{d}t^2} = -\frac{Ze}{mc} \left(\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} \times \nabla U \right),\tag{3.30}$$

where $m = m_o (1 - v^2/c^2)^{-1/2}$. Let us transform Eq. 3.30 to the differentiation over trajectory path *s* (remember that ds = vdt, v = const); as a result, we obtain

$$\frac{\mathrm{d}^2 \mathbf{r}}{\mathrm{d}s^2} = \frac{Ze}{mvc} \left(\nabla U \times \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}s} \right). \tag{3.31}$$

The solution of Eq. 3.31 is determined by the value of particle rigidity Ze/mvc and the space distribution of the magnetic field.

At large distances from the earth $(r \ge 3r_E)$ the magnetic field can be accurately considered as an axial-symmetric field of the magnetic dipole. From Table 3.1 it can

be seen that at these distances the role of the highest harmonics is smaller than 5%, i.e., the influence of the highest harmonics and outer sources can be considered as some small perturbation to the main dipole field. It means that for the real geomagnetic field an "approximate integral" can be found which can be considered as an analog of the Störmer integral for a dipole field (see Chapter 2). Therefore, at these distances the so-called Störmer method can be used (see Section 3.4.2).

On the distances $r < 3r_{\rm E}$ for particles with rigidity smaller than 3–5 GV, the curvature radius of the particle trajectory will be smaller than the scale of the magnetic field's change and, in this case, can be used in the drift approximation describing the moving of the center of a particle rotating in the magnetic field. The method of drift approximation for particles moving in the geomagnetic field was applied for the first time by H. Alfvén (see Alfvén, M1950; see also Pikelner, M1966); therefore, this method is often called the Alfvén method (see Section 3.4.3).

3.4.2 Störmer Method

The Störmer method was used in many calculations of CR asymptotic directions and cutoff rigidities in the real geomagnetic field (e.g., Quenby and Webber, 1959; Webber, 1963; Ray, 1963a; Stern, 1967). Ray (1963a) and Stern (1967) considered this method in more detail.

Let us describe magnetic field *H* by vector potential A; it can be produced with accuracy for the gradient of any scalar function $\varphi(\mathbf{r})$. Let us choose the gradient of $\varphi(\mathbf{r})$ so that scalar product AH = 0, i.e.,

$$\mathbf{A} \cdot \nabla \times \mathbf{A} = 0. \tag{3.32}$$

The solution of this equation can be written as follows:

$$\mathbf{A} = \boldsymbol{\alpha}(\mathbf{r}) \,\nabla \boldsymbol{\beta}\left(\mathbf{r}\right),\tag{3.33}$$

where $\alpha(\mathbf{r})$ and $\beta(\mathbf{r})$ are scalar functions from the coordinates. On the other hand, as we mentioned above, in the region without electrical currents, magnetic field *H* can be described by the scalar potential *U*, i.e, $H = \nabla U$. Three scalar functions α , β , *U* can be chosen as the basis for the natural system of coordinates connected with the magnetic field. Really,

$$H = \nabla \times \mathbf{A} = \nabla \alpha \times \nabla \beta, \qquad (3.34)$$

i.e., vectors $\nabla \alpha$ and $\nabla \beta$ are perpendicular to *H*, which is equal to ∇U . This may be written as

$$\nabla U \cdot \nabla \alpha = \nabla U \cdot \nabla \beta = 0. \tag{3.35}$$

For determining the equation for a charged particle moving in this curvilinear system of coordinates, let us find the Lagrangian of this system:

3 Cosmic Rays in the Real Geomagnetic Field

$$L = \frac{mv^2}{2} + \left(\frac{Ze}{c}\right) \mathbf{v} \cdot \mathbf{A}, \qquad m = \left(1 - v^2/c^2\right)^{-1/2}.$$
 (3.36)

In the Descartes orthogonal system of coordinates we obtain

$$v^2 = \dot{x}^2 + \dot{y}^2 + \dot{z}^2, \qquad (3.37)$$

and consider x, y, and z as functions of α , β , U. Making differentiation and using Eq. 3.34, we obtain

$$v^{2} = \left[\left(\frac{\partial x}{\partial \alpha} \right)^{2} + \left(\frac{\partial y}{\partial \alpha} \right)^{2} + \left(\frac{\partial z}{\partial \alpha} \right)^{2} \right] \dot{\alpha}^{2} + \left[\left(\frac{\partial x}{\partial \beta} \right)^{2} + \left(\frac{\partial y}{\partial \beta} \right)^{2} + \left(\frac{\partial z}{\partial \beta} \right)^{2} \right] \dot{\beta}^{2} + \left[\left(\frac{\partial x}{\partial U} \right)^{2} + \left(\frac{\partial y}{\partial U} \right)^{2} + \left(\frac{\partial z}{\partial U} \right)^{2} \right] \dot{U}^{2} + 2 \left[\left(\frac{\partial x}{\partial \alpha} \right) \left(\frac{\partial x}{\partial \beta} \right) + \left(\frac{\partial y}{\partial \alpha} \right) \left(\frac{\partial y}{\partial \beta} \right) + \left(\frac{\partial z}{\partial \alpha} \right) \left(\frac{\partial z}{\partial \beta} \right) \right] \dot{\alpha} \dot{\beta}.$$
(3.38)

After calculating the derivatives in Eq. 3.38, we obtain

$$v^{2} = \frac{A^{2}}{\alpha^{2}H^{2}}\dot{\alpha}^{2} + \frac{|\nabla\alpha|}{H^{2}}\dot{\beta}^{2} + \frac{1}{H^{2}}\dot{U}^{2} - 2\frac{\mathbf{A}\cdot\nabla\alpha}{\alpha H^{2}}\dot{\alpha}\dot{\beta}.$$
 (3.39)

Because $\dot{\boldsymbol{\beta}} = \nabla \boldsymbol{\beta} \cdot \mathbf{v} = |\nabla \boldsymbol{\beta}| v_{\boldsymbol{\beta}}$, it follows that

$$\mathbf{A} \cdot \mathbf{v} = |\mathbf{A}| \, v_{\beta} = \alpha \beta. \tag{3.40}$$

Substituting Eqs. 3.39 and 3.40 into Eq. 3.36, we obtain

$$L = \frac{m}{2} \left[\frac{A^2}{\alpha^2 H^2} \dot{\alpha}^2 + \frac{|\nabla \alpha|}{H^2} \dot{\beta}^2 + \frac{1}{H^2} \dot{U}^2 - 2 \frac{\mathbf{A} \cdot \nabla \alpha}{\alpha H^2} \dot{\alpha} \dot{\beta} \right] + \frac{Ze}{c} \alpha \dot{\beta}.$$
(3.41)

If the Lagrangian in the natural system of coordinates is known, it is easy to determine the integrals of a moving particle connected with the symmetry of the magnetic field. For example, let us consider the field of a magnetic dipole. In this case

$$A_r = A_{\theta} = 0, \quad \alpha = rA_{\varphi}(r,\theta)\sin\theta, \quad \beta = \varphi, \quad H = |\alpha| |\beta|.$$
(3.42)

Substituting Eq. 3.42 into Eq. 3.39 shows that *L* does not depend on φ . In this case, according to Eq. 2.3 (see Chapter 2), we obtain the integral $\partial L/\partial \varphi = \text{const.}$ By differentiating, we will find that this integral coincides with Störmer's integral determined by Eq. 2.10. The real geomagnetic field is quasi-symmetrical, i.e., very weak depending on one of the coordinates: $\partial L/\partial \beta \approx 0$. Let us assume that $\partial L/\partial \beta = 0$. In this case, $\partial L/\partial \dot{\beta} = \text{const.}$ By differentiating Eq. 3.39 over $\dot{\beta}$, we obtain

3.4 Analytical Methods of Trajectory Calculations in the Real Geomagnetic Field

$$m\left[\frac{|\nabla\alpha|^2}{H^2}\dot{\beta} - \frac{\mathbf{A}\cdot\nabla\alpha}{\alpha H^2}\dot{\alpha}\right] + \frac{Ze}{c}\alpha = \text{const.}$$
(3.43)

Let us determine angles η , ω , ξ as follows:

$$\mathbf{v} \cdot \nabla \alpha = v |\nabla \alpha| \cos \eta, \mathbf{v} \cdot \nabla \beta = v |\nabla \beta| \cos \omega, \nabla \alpha \cdot \nabla \beta = |\nabla \alpha| \cdot |\nabla \beta| \cos \xi. \quad (3.44)$$

In this case, Eq. 3.43 can be rewritten as

$$mv\frac{A|\nabla\alpha|^2}{\alpha H^2}\left(\cos\omega - \cos\eta\cos\xi\right) + \frac{Ze}{c}\alpha = \text{const.}$$
 (3.45)

According to the cosine spherical law,

$$\cos\omega - \cos\eta\cos\xi = \sin\eta\sin\xi\cos\Phi, \qquad (3.46)$$

where Φ is the bi-plane angle between planes $(\nabla \alpha, \nabla \beta)$ and $(\nabla \alpha, \mathbf{v})$.

Let us express vector-potential through the magnetic field H:

$$A = \alpha |\nabla\beta| = \frac{\alpha |\nabla\beta| |\nabla\alpha| \sin\xi}{|\nabla\alpha| \sin\xi} = \frac{\alpha H}{|\nabla\alpha| \sin\xi},$$
(3.47)

and introduce this expression into Eq. 3.45. We obtain

$$mv\left(|\nabla \alpha|/H\right)\cos\psi + \left(\frac{Ze}{c}\right)\alpha = \text{const},$$
 (3.48)

where

$$\cos \psi = \sin \eta \cos \Phi. \tag{3.49}$$

Let us introduce Störmer's units of length by taking the value $(MZe/mcv)^{-1/2}$ for the unit of length, where *M* is some constant characterized magnetic field with the measurability of the magnetic dipole moment. In these units, Eq. 3.45 will be transformed into

$$(|\nabla \alpha|/H)\cos\psi + \alpha = 2\gamma$$
 (3.50)

or

$$\cos \psi = (2\gamma - \alpha) H / |\nabla \alpha|. \tag{3.51}$$

The integral described by Eq. 3.51 is an approximate integral of a particle moving in a quasi-symmetrical magnetic field; it can be considered as an analog of Störmer's integral for a dipole field (see Chapter 2). For practical use of the integral Eq. 3.51 it is necessary to find function α for the real magnetic field. In the general case, this function must be determined by the solution of the differential Eq. 3.34 in partial derivatives. However, in some important partial cases, function α can be found by an easier way. Detailed extended calculations of functions α and β (so-called Euler potentials) were made by Stern (1967a, b) for the earth's magnetic field caused by inside and outside sources. The investigation of a charged particle moving in the real geomagnetic field by using Euler potentials was also carried out by Ray (1963a).

3.4.3 Alfvén Method

Let us consider the moving of a charged particle in a magnetic field under the Lorenz force and some other force f. The equation describing this moving

$$m\dot{\mathbf{v}} = \frac{Ze}{c}\mathbf{v} \times \mathbf{H} + \mathbf{f}$$
(3.52)

can be simplified by the substitution

$$\mathbf{v} = \mathbf{v}_{1g} + \mathbf{v}_1, \tag{3.53}$$

where

$$\mathbf{v}_{1g} = \frac{c}{ZeH^2} \mathbf{f} \times \mathbf{H}.$$
 (3.54)

Because

$$\frac{Ze}{c} \left| \mathbf{v}_{1g} \times \mathbf{H} \right| = \frac{1}{H^2},\tag{3.55}$$

the Eq. 3.52 will be transformed into

$$m\dot{\mathbf{v}}_1 = \frac{Ze}{c}\mathbf{v}_1 \times \mathbf{H} - m\dot{\mathbf{v}}_{1g} = \frac{Ze}{c}\mathbf{v}_1 \times \mathbf{H} + \mathbf{f}_i, \qquad (3.56)$$

where $\mathbf{f}_i = -m\dot{\mathbf{v}}_{1g}$ presents the inertia force. Let us now assume that

$$\mathbf{v}_1 = \mathbf{v}_{2g} + \mathbf{v}_2, \tag{3.57}$$

where

$$\mathbf{v}_{2g} = \frac{c}{ZeH^2} \mathbf{f}_i \times \mathbf{H}.$$
 (3.58)

In this case we obtain the equation

$$m\dot{\mathbf{v}}_2 = \frac{Ze}{c}\mathbf{v}_2 \times \mathbf{H} - m\dot{\mathbf{v}}_{2g},\tag{3.59}$$

which is an analog of Eq. 3.56. This process can be continued up to some number k,

$$m\dot{\mathbf{v}}_k = \frac{Ze}{c} \mathbf{v}_k \times \mathbf{H} - m\dot{\mathbf{v}}_{kg}, \qquad (3.60)$$

when the Lorenz radius becomes much smaller than the scale of the magnetic field change. In this case

$$\frac{Ze}{c}\mathbf{v}_k \times \mathbf{H} \gg \frac{\mathrm{d}}{\mathrm{d}t} \frac{mc}{ZeH^2} \mathbf{f}_i \times \mathbf{H}, \qquad (3.61)$$

and, by the second member in Eq. 3.60, may be neglected. Now the moving of a charged particle in the real magnetic field can be resolved by three components:

- 1. The fast cyclotron rotation around the magnetic force line
- 2. Drift moving of the center of the cyclotron circle across the magnetic field with the velocity

$$\mathbf{v}_g = \mathbf{v}_{1g} + \mathbf{v}_{2g} + \dots + \mathbf{v}_{kg} = \frac{c}{ZeH^2} \left(\left(\mathbf{f} + \mathbf{f}_{ik} \right) \times \mathbf{H} \right),$$
(3.62)

where $\mathbf{f}_{ik} = -m d\mathbf{v}_g / dt$

3. Free movement along the magnetic force line described by the equation

$$m \mathrm{d} \mathbf{v}_{||} / \mathrm{d} t = \mathbf{f}_{||} \tag{3.63}$$

Let us note that the cyclotron rotation of a charged particle around the magnetic force line generates a magnetic field which is equal to the field of a magnetic dipole with moment

$$\mu = m v_\perp^2 / 2H. \tag{3.64}$$

The value of the magnetic moment determined by Eq. 3.64 is approximately an integral of a particle moving in a magnetic field and is usually called "the first adiabatic invariant." Potential energy E_{μ} of the magnetic dipole in the magnetic field is determined by the expression

$$E_{\mu} = \mu H, \tag{3.65}$$

and the force acting on the particle will be

$$\mathbf{f} = -\mu \nabla H. \tag{3.66}$$

Substituting Eq. 3.66 into Eqs. 3.62 and 3.63, we obtain the equation in the drift approximation for moving the leader center of a charged particle in the nonhomogeneous magnetic field. Let us account that in Eq. 3.62, the force f also enters the perpendicular component of inertia force $f_{i\perp}$ and centrifugal force f_c formatting when particle moving with velocity $v_{||}$ along the bending magnetic force line. If ρ is the radius of curvature of magnetic force line,

$$f_c = m v_{||}^2 / \rho. \tag{3.67}$$

Calculating forces determined by Eqs. 3.66 and 3.67 for the field of magnetic dipole and substituting the obtained expressions in Eqs. 3.62 and 3.63, after cumbersome but simple calculations, we obtain as following:

$$\frac{\mathrm{d}\lambda}{\mathrm{d}t} = \left(\frac{2\mu}{mr_{eq}^3} \frac{H_o - H}{\cos^2 \lambda \left(1 + 3\sin^2 \lambda\right)}\right)^{1/2},\tag{3.68}$$

$$\frac{\mathrm{d}\varphi}{\mathrm{d}t} = \frac{3c\mu}{Zer_{eq}^2} \frac{1+\sin^2\lambda}{\cos^4\lambda \left(1+3\sin^2\lambda\right)^{3/2}} \frac{H_o-H}{H},\tag{3.69}$$

where r_{eq} is the equatorial distance of the magnetic force line and $H_o = E_k/\mu$ is the value of the magnetic field at the reflection point of a particle with kinetic energy E_k . It is now possible to determine the trajectory of the particle:

$$\varphi - \varphi_o = \bar{I}\left(\frac{r_{eq}}{S}\right),\tag{3.70}$$

where S is the Störmer unit of length, and

$$\bar{I} = \frac{3}{2} \int_{0}^{\lambda} \frac{\cos^3 \lambda \left(1 + \sin^2 \lambda\right)}{\left(1 + 3\sin^2 \lambda\right)^{3/2}} \frac{2H_o - H}{H_o - H} \mathrm{d}\lambda.$$
(3.71)

The connection between λ and \overline{I} for different latitudes of refraction λ_o was calculated by Alfvén (M1950) and is shown in Fig. 3.1.

The moving of the leader center described by Eqs. 3.70 and 3.71 can be applied only to the dipole magnetic field. However, if the magnetic field force lines are known, the calculation of trajectories in the drift approximation is not difficult. Namely, in the real geomagnetic field, the charged particle will move along the force lines with the azimuthal drift which depends on the gradient of the magnetic field and curvature of the magnetic field force lines. Because the main part of the geomagnetic field is the dipole field, for the calculation of drift Eqs. 3.70 and 3.71 may be used with small corrections.



Fig. 3.1 The connection between displacement along longitude (proportional to \overline{I}) and displacement along latitude λ for charged particle oscillated relative to the equatorial plane with the amplitude characterized by the latitude of reflection λ_{ρ}

3.4.4 Peculiarities at High Latitudes; Using Boltzmann Equation

Thanks to numeral experimental investigations on satellites with polar orbits (see, e.g., Akasofu et al., 1963), it was found that the region of latitudes higher than $60-70^{\circ}$ is practically open for the access of very small energy solar and galactic CR. It means that the conception of CR cutoff rigidity does not exist for this region and the above-considered analytical methods do not work. The main cause of this phenomenon is small energy particle-scattering by magneto-hydrodynamic waves in the outer magnetosphere, and especially in the tail of the magnetosphere. As a result, by a diffuse process, small energy particles can enter inside the magnetosphere at any point above $60-70^{\circ}$ latitude. For calculation of energetic charged-particle distribution in the outer magnetosphere and their intrusion into the polar cap it is necessary to use Boltzmann's kinetic equation taking into account collisions:

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} + \frac{Ze}{c}\left(\mathbf{v}\times\mathbf{H}\right)\frac{\partial f}{\partial \mathbf{v}} = \left(\frac{\partial f}{\partial t}\right)_{\rm col},\tag{3.72}$$

where $f \equiv f(\mathbf{r}, \mathbf{v}, t)$ is the distribution function, and the right part of Eq. 3.72 describes the collision of particles with magneto-hydrodynamic waves. Let us note that Eq. 3.72 is valid until the energy density of CR particles is much smaller than the energy density of the magnetic field in the region of particle propagation (if not, it is necessary to solve the self-consistent problem: to take into account non-linear effects – pressure of energetic particles and kinetic-stream instability, see Section 3.4.5).

3.4.5 The Case of High CR Energy Density in the Outer Magnetosphere and the Self-Consistent Nonlinear Problem

In all above-considered cases, it was assumed that the energy density of the charged energetic particles is much smaller than the energy density of geomagnetic field $H^2/8\pi$ and we considered the moving of a single particle, the behavior of which in the geomagnetic field does not depend on the existence of other charged energetic particles. It is absolutely true for galactic CRs with an energy density not more than few eV/cm³. However, for a trapped population of energetic particles and in some cases of great solar CR events, we have a different situation with a controversy relation, when the CR energy density is comparable to or bigger than the energy density of the magnetic field, especially in the outer magnetosphere. In this case, it is necessary to take into account the self-magnetic field of energetic particles and consider the nonlinear self-consistent problem. It became important to account the pressure of charged energetic particles, and in the case of energetic particle anisotropy, it was also important to consider kinetic-stream instabilities in the background plasma with additional generation of magneto-hydrodynamic waves on which energetic particles scattered (see details in Chapter 3 in Dorman, M2006).

3.4.6 Regions of Applicability of Analytical Methods

As we mentioned in Sections 3.4.4 and 3.4.5, in the region above geomagnetic latitude 60–70°, the concept of cutoff rigidity is not valid. The remaining region can be approximately separated into three zones: (1) $60^\circ > \lambda > 40^\circ$, (2) $40^\circ > \lambda > 20^\circ$, and (3) $20^\circ > \lambda > 0^\circ$.

For the first zone, $60^\circ > \lambda > 40^\circ$ in the high altitudes can be neglected by highest harmonics of the geomagnetic field, and on the lower altitudes the drift method can be used. The condition for conversion of the first adiabatic invariant for using the drift method is

$$r_L \nabla H/H \ll 1$$
, or $5 \times 10^{-2} R (r/r_E)^2 \ll 1$, (3.73)

where $r_{\rm L} = p_{\perp} c/ZeH$ is the Larmor radius, and R is the particle rigidity in GV.

For the second zone, $40^{\circ} > \lambda > 20^{\circ}$ analytical methods are not valid and cutoff rigidities can be estimated approximately by interpolation of results obtained in the first and third zones (Quenby and Webber, 1959). For more exact results and taking into account sufficient for this penumbra region, it is necessary to make numerical calculations of CR trajectories through 0.01 GV, or more exactly, through 0.001 GV.

For the third zone, $20^{\circ} > \lambda > 0^{\circ}$ for approximate calculations of cutoff rigidities, Störmer's analytical method can be used. However, asymptotic directions for this region can be found only by numerical calculations of CR trajectories.

3.5 Main Methods of Numerical Calculation of Charged-Particle Trajectories in the Real Geomagnetic Field

3.5.1 Gauss Coefficients and Expected Accuracy of Numerical Calculation of Trajectories in the Real Geomagnetic Field; Comparison with that Expected for Dipole Field

As is well known, there are no analytical expressions for CR trajectories, even in the dipole approximation of the geomagnetic field (excluding trajectories in the equatorial plane). CR trajectories in the geomagnetic field can be determined in two ways: (1) by model experiment (Malmfors, 1945; Brunberg and Dattner, 1953), and (2) by numerical calculations (Störmer, M1955; Jory, 1956; Lüst, 1957; Lüst and Simpson, 1957; and many others).

The system of equations determining the charged particle moving in any magnetic field will be

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{Ze}{c} \left(\mathbf{v} \times \nabla U\right), \qquad \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} = \mathbf{v}. \tag{3.74}$$

n	т	Finch and L	eaton (1957)	Adam et al. (1964a)			
		$g_n^m, \ 10^{-4} Gs$	$h_n^m, \ 10^{-4} Gs$	$g_n^m, \ 10^{-4} Gs$	$h_n^m, \ 10^{-4} Gs$		
1	0	-3055	0	-3046	0		
1	1	-227	+590	-232	+581		
2	0	-152	0	-114	0		
2	1	+303	-190	+303	-194		
2	2	+158	+24	+167	+32		
3	0	+118	0	+113	0		
3	1	+191	-45	-177	-44		
3	2	+126	+29	+115	+20		
3	3	+91	-9	+80	-14		
4	0	+95	0	+104	0		
4	1	+80	+15	+87	+13		
4	2	+58	-31	+46	-31		
4	3	-38	-4	-31	-1		
4	4	+31	-17	+32	-23		
5	0	-27	0	-23	0		
5	1	+32	+2	+22	+1		
5	2	+20	+10	+4	+12		
5	3	-4	-5	-8	-7		
5	4	-15	-14	-14	-11		
5	5	-7	+9	-7	+7		
6	0	+10	0	+10	0		
6	1	+5	-2	+22	-3		
6	2	+2	+11	-16	+12		
6	3	-24	0	-22	+3		
6	4	-3	-1	-3	-1		
6	5	0	-3	+1	-1		
6	6	-11	-1	-10	-1		

Table 3.2 Gauss coefficients g_n^m , h_n^m for the epoch 1955 according to Finch and Leaton (1957) and Adam et al. (1964a) in CGSM units

If the Gauss coefficients, g_n^m , h_n^m , are known (e.g., Table 3.2), the strength of the real geomagnetic field in Eq. 3.74, $\mathbf{H} = -\nabla U$, can be calculated very easily according to Eqs. 3.18–3.20.

Because the Gauss coefficients g_n^m , h_n^m are known with some definite accuracy, for control of the trajectory, numerical calculations are necessary to make these calculations for different groups of Gauss coefficients and then to compare the results. Table 3.2 gives Gauss coefficients g_n^m , h_n^m for the epoch 1955, according to Finch and Leaton (1957), based on maps of the British Admiralty, and Adam et al. (1964a) based on maps of IZMIRAN (Moscow region, Russia). On the basis of groups of Gauss coefficients g_n^m , h_n^m for the epoch 1955.0, according to Finch and Leaton (1957) and Adam et al. (1964a), in Dorman et al. (1966), trajectories of CR in the rigidity interval from 1 to 10.5 GV are numerically calculated. As an example, in Fig. 3.2 are shown asymptotic directions for the Russian CR station Mirny in Antarctica for both groups of Gauss coefficients and for dipole approximation.

It can be seen in Fig. 3.2 that the difference between asymptotic directions for Gauss coefficients g_n^m , h_n^m according to Finch and Leaton (1957) and Adam et al. (1964a), is not more than 1–2° in longitude and latitude. From Fig. 3.2 it can be also seen that the asymptotic directions found for the real field described in Finch and Leaton (1957) and Adam et al. (1964a), are shifted by about 20° to the west relative to the asymptotic directions found for the dipole approximation of the geomagnetic field (let us note that the magnetic force line corresponding to CR station Mirny in the real magnetic field has also shifted by 20° relative to the force line in the dipole approximation).

The other example is shown in Fig. 3.3: for CR station Tixie Bay in the north of Siberia in Russia (for particles with rigidities from 1 to 106 GV).

From Fig. 3.3 it can be again seen that, though the asymptotic directions for real and dipole magnetic field are situated on one smooth curve (like Störmer's



curve in Fig. 2.4), the asymptotic directions for small rigidities (about 1 GV) for the real geomagnetic field are shifted in longitude for more than 100° relative to asymptotic directions for the dipole field. So, the different presentations of the real geomagnetic field for the same epoch gave about the same asymptotic directions (with an accuracy of about $1-2^{\circ}$), but the difference between asymptotic directions in the real geomagnetic field and in the dipole field is several tens of degrees.

3.5.2 Störmer's Method of Numerical Calculation of Trajectories in Dipole Geomagnetic Field: Why it cannot be Used for Real Geomagnetic Field

Störmer (M1955) developed a relatively simple method of numerical calculation of CR trajectories in the dipole geomagnetic field, based on well-known difference methods of integration of ordinary differential equations supposed by Adams (see details in Berezin and Zhidkov, M1959; Mysovskikh, M1962; Lans, M1962). The Adams method was applied by Störmer (M1955) for solving equations of the type

$$\frac{\mathrm{d}^2 \mathbf{r}}{\mathrm{d}t^2} = \mathbf{F}(\mathbf{r}), \qquad (3.75)$$

where, in the right hand, the force does not depend on $\dot{\mathbf{r}}$, i.e., it does not depend on the particle velocity (in difference from Eq. 3.74). By using a cylindrical system of coordinates, the equation of a charged particle moving in any axial-symmetric magnetic field can be transferred to the equation of a particle moving in some potential field in which, as is well known, the force does not depend on the particle velocity. In particular, the system of equations of a particle moving in the cylindrical system of coordinates for the dipole magnetic field is described in Chapter 2 (see Eq. 2.15).

When we consider the real geomagnetic field, it is necessary to take into account not only the dipole field but also higher spherical harmonics. In this case, the magnetic field will not be axial-symmetric and therefore Eq. 3.75 cannot be transformed to Eq. 2.15. This is the main reason why Störmer's method (M1955) cannot be applied to numerical calculations of CR trajectories in the real geomagnetic field.

3.5.3 Method Runge–Kutta of Fourth Order for Numerical Calculations of CR Trajectories in Real Geomagnetic Field

In many papers, relating to numerical calculations of CR trajectories in the real geomagnetic field, the well-known Runge–Kutta fourth-order method in computation mathematics is used. From the theory of differential equations it is known that any system of ordinary differential equations can be, by changing the variables, transformed into a system of first-order differential equations. Moreover, any method of numerical integration of one differential equation can be automatically applied for the solution of the system of differential equations. Therefore, to avoid cumbrous and complicated formulas, let us consider, instead of the system of second-order differential equations, only one equation of the first order

$$y' = f(x, y),$$
 (3.76)

which satisfies the initial condition $y = y_o$ at $x = x_o$. An unknown solution in the neighborhood of point $x = x_o$ can be found by the Taylor series:

$$y(x) = y_o + \frac{y'_o}{1!}(x - x_o) + \frac{y''_o}{2!}(x - x_o)^2 + \dots + \frac{y_o^{(n)}}{n!}(x - x_o)^n + O\left(|x - x_o|^{n+1}\right),$$
(3.77)

where $O\left(|x-x_o|^{n+1}\right)$ is the remainder term of the n+1 order of trifle. Let us choose the value of the initial step of integration as $x - x_o = h$ and neglect the remainder member of the n+1 order of trifle. In this case, on the basis of Eq. 3.77, we can calculate the value of the unknown function y at point $x = x_o + h$:

$$y(x_o+h) = y_o + \frac{y'_o}{1!}h + \frac{y''_o}{2!}h^2 + \dots + \frac{y_o^{(n)}}{n!}h^n.$$
 (3.78)

Repeating this process step by step, we can find the integral curve of Eq. 3.76, and in the case of the system of equations described by Eq. 3.75 – the trajectory of a particle. Derivatives in Eq. 3.78 can be found by differentiation of the initial Eq. 3.76:

$$y'_{o} = f(x_{o}, y_{o}) = f_{o}, \quad y''_{o} = \frac{df_{o}}{dx} + f_{o}\frac{df}{dy}, \dots$$
 (3.79)

For the described method the most difficult part is the calculation of higher-order derivatives according to Eq. 3.79 (it can be limited only by derivatives of the second order and, in this case, we obtain the method of Euler tangents which was used as a basis of Störmer's method, described in Chapter 2).

To avoid calculations of higher-order derivatives and taking into account a possibly larger number of members of the series of Eq. 3.77, it is convenient to use the well-known Runge–Kutta method (see Berezin and Zhidkov, M1959; Mysovskikh, M1962; Lans, M1962; Press et al., M1992). This method supposes to present the solution in the following linear combination:

$$y(x) = y(x_o) + a_1k_1(x - x_o) + a_2k_2(x - x_o) + \dots + a_nk_n(x - x_o) + O\left(|x - x_o|^{n+1}\right),$$
(3.80)

where

$$\begin{cases} k_1 (x - x_o) = (x - x_o) f (x_o, y_o); \\ k_2 (x - x_o) = (x - x_o) f (x + b_1 (x - x_o), y_o + c_{21}k_1); \\ \dots \\ k_n (x - x_o) = (x - x_o) f (x + b_{n-1} (x - x_o), y_o + c_{n1}k_1 + \dots + c_{nn-1}k_{n-1}). \end{cases}$$
(3.81)

Coefficients a_i , b_i , c_{ij} are some constants, which are chosen so that the difference between the series Eq. 3.77 and Eq. 3.80 becomes minimal, i.e., the remaining members of both series must be one order of trifle. This condition led to the system of algebraic equations for determining coefficients a_i , b_i , c_{ij} . Calculations show that at $n \ge 5$ the accuracy does not increase, so it is enough to use the method Runge–Kutta of fourth order of accuracy. Now, because we know the initial condition $y|_{x=x_0} = y_0$, and choosing the step $x - x_0 = h$, it is easy to start the process of integration:

$$y(x_{o}+h) = y(x_{o}) + a_{1}k_{1}(h) + a_{2}k_{2}(h) + \dots + a_{n}k_{n}(h).$$
(3.82)

Comparison of Eq. 3.82 with Eq. 3.78 shows that instead of calculations of derivatives $y^{(i)}$ up to order *n*, we need to calculate the function values of the initial equation at different points, which is a much simpler problem.

3.5.4 The Choice of the Value of the Step of Numerical Integration: The Gill's Modification

The main difficulty of the Runge–Kutta method is the estimation of the error of calculations that is necessary for determining the value of the step of integration. To overcome this difficulty, Gill (1951) supposed using the method of subdivision of the step: after obtaining the solution at the next point by step h, the calculations are repeated at step h/2 and the obtained solutions are compared. If both solutions are identical in the frame of the chosen accuracy, in further calculations the larger step h will be used; if they are different, the calculation is repeated at step h/2, and so on. This method can be effective when the value of the step is constant: after choosing the step at the beginning of integration, the same step can be used along the full trajectory.

For the real geomagnetic field, the situation is more complicated because, in this case, it is necessary to obtain at each step about the same accuracy necessary to sufficiently increase the value of the step with an increasing of distance from the earth; e.g., for the integration of the trajectory of the negative particle with rigidity 10.5 GV started vertically from 20 km altitude above the earth's surface at geomagnetic latitude $\lambda = 65^{\circ}$ to obtain the error 0.01° in the direction necessary to use the step 350 km at the beginning of integration and 7,000 km at the end (at a distance of about 25 $r_{\rm E}$). Of course, it is possible to use the minimal step 350 km during total integration, but in this case, the time of numerical calculations will be increased about 10 times. Nevertheless, this method was widely used in many numerical calculations of CR trajectories in the real geomagnetic field (see, e.g., McCracken, 1962; McCracken and Freon, 1962; McCracken et al., 1962, M1965; Shea et al., 1965a, b).

3.5.5 Kelsall's Modification of the Runge-Kutta Method

To minimize the time of numerical calculations of CR trajectories in the real geomagnetic field and to obtain at each step about the same accuracy, Kelsall (1961) came to the conclusion that the value of step h must be chosen as follows:

$$h = \begin{cases} 0.2, & \text{if} \quad \rho \ge 10, \\ 0.02\rho, & \text{if} \quad \rho < 10, \end{cases}$$
(3.83)

where ρ is the radius of the curvature of the trajectory (here steps *h* and ρ are in Störmer's units of length). The separating of the region of integration on two regimes corresponds to using Störmer's method ($\rho \ge 10$) and Alfvén's method ($\rho < 10$) which were described in Sections 3.4.2 and 3.4.3.

3.5.6 The Merson's Modification of the Runge–Kutta Method

At integration of the differential equation by the Runge–Kutta method of fourthorder accuracy, the error of each step of computations is determined by the fifth member in the Taylor series, which is equal to $f_o^{(5)}h^5/120$. As we mentioned above, the calculations of high-order derivatives are met with difficulties. In Merson's modification of the Runge–Kutta method (see the detailed description in Lans, M1962) it is shown that the computation of the fifth-order derivative of function f can be transformed to the additional calculation of function f at some known point. The following formula is used for this modification:

$$y(x_o+h) = y(x_o) + \frac{1}{6} [k_1(h) + 4k_4(h) + k_5(h)] + O(h^5), \qquad (3.84)$$

where

$$\begin{cases} k_{1} = hf(x_{o}, y_{o}), \\ k_{2} = hf(x_{o} + \frac{h}{3}, y_{o} + k_{1}), \\ k_{3} = hf(x_{o} + \frac{h}{3}, y_{o} + \frac{k_{1}}{2} + \frac{k_{2}}{2}), \\ k_{4} = hf(x_{o} + \frac{h}{2}, y_{o} + \frac{3k_{1}}{8} + \frac{9k_{3}}{8}), \\ k_{5} = hf(x_{o} + h, y_{o} + \frac{3k_{1}}{2} - \frac{9k_{3}}{2} + 6k_{4}), \end{cases}$$

$$(3.85)$$

and the error of integration is determined by the formula

$$\varepsilon = \frac{1}{5} \left(k_1 - \frac{9}{2} k_3 + 4k_4 - \frac{1}{2} k_5 \right).$$
(3.86)

From Eq. 3.86 it follows that the error of integration is proportional to h^5 , i.e.,

$$\boldsymbol{\varepsilon} = ah^5; \quad h = (\boldsymbol{\varepsilon}/a)^{1/5}, \tag{3.87}$$

where *a* is some constant. If the error ε of trajectory integration is given, it is easy to determine the necessary value of step *h*: let us choose some arbitrary step *h*₁ and then, by Eqs. 3.85 and 3.86, we calculate the corresponding error ε_1 . Now on the basis of Eq. 3.87 it is easy to determine the necessary step *h*:

. ...

$$h = h_1 \left(\varepsilon_1 / \varepsilon \right)^{1/5}. \tag{3.88}$$

In Dorman and Smirnov (1966a, 1967), two programs were compounded for integration of CR trajectories in the real geomagnetic field presented by six spherical harmonics. In the first program, the integration was made according to Gill's modification (see Section 3.5.4), and in the second, – according to that described here – Merson's modification. A comparison of the obtained results shows that Merson's modification needed several times less time for computing and gave more exact results than Gill's modification. This is caused mainly by the important peculiarity of Merson's modification: control of the obtained error at each step of trajectory integration.

3.5.7 The Stability of CR Trajectory Integration and Control of Accuracy

The computation of the error at each step of integration does not determine the final accuracy of CR trajectory calculation. The problem of the accuracy of the solution is closely connected with the problem of stability: How did the final result change after small changes of the initial conditions? As was shown in Section 2.12, for the dipole magnetic field in the region of high latitudes, the well-known effect of particles focusing takes place in the geomagnetic field. This means that CR energetic charged particles that arrived at some point in the frame of some small space angle $\Delta \omega$ have smaller space angle $\Delta \Omega$ outside the geomagnetic field, i.e., the value M = $\Delta \omega / \Delta \Omega > 1$, and for some resonant rigidities $M \gg 1$. In this case, the integration of the trajectory of a negative-charged particle starting from the earth's surface will be stable: even big errors in the initial vector of the particle velocity vector will not lead to sufficient errors in the calculated asymptotic direction. According to Boström (1964), the value M > 1 at all latitudes except some small latitude interval near the Equator. This means that the stability of CR trajectory integration is expected for a particle arriving at any point of the earth's surface. Although this result was obtained for the dipole magnetic field, it is also correct approximately for the real geomagnetic field where the dipole component is more than 80% of the total field.

In many papers two methods are used for the control of the accuracy of trajectory computation: (1) checking the particle velocity, which must be invariant, and (2) inverse integration. The first method gave control of the constant (with an accuracy of about 1%) only of the module of velocity $v^2 = \dot{x}^2 + \dot{y}^2 + \dot{z}^2$, but not direction. As was shown in Dorman and Smirnov (1966a, 1967), even at a constant particle velocity with an error smaller than 1%, the errors in direction reached up to 10°. Much better results gave the inverse integration. The process of inverse integration is as follows: the direct integration of the trajectory takes a negative-charged particle from the earth's surface and continues up to distances where the influence of the geomagnetic field becomes negligible, and then starts integration for the positive particle with the same rigidity in an inverse direction to the earth's surface. In Dorman et al. (1966), Dorman and Smirnov (1966a, 1967), Merson's modification of the Runge–Kutta method and inverse integration for the control of final results were used: if the difference in initial and final velocity vectors is more than 0.15°, the trajectory integration repeated with error ε in Eq. 3.86 is two times smaller.

3.5.8 Numerical CR Trajectory Integration in Spherical Geographical System of Coordinates

Because the scalar potential of the real geomagnetic field is usually given as a function of geographical coordinates, it is convenient to use for numerical trajectory computation the geographical spherical system of coordinates with polar axis coinciding with the axis of the earth's rotation (see Fig. 3.4).

In Dorman et al. (1966) and Dorman and Smirnov (1966a, 1967) the differentiation over time was transferred to differentiation over the length of the arch and the following units chosen: for particle rigidity 1 GV, for the strength of geomagnetic field 10 gammas (10^{-4} Gs), for distance 10^3 km. By using these units, the system of equations described by Eq. 3.74 will be transformed to the following system:



Fig. 3.4 The geographical spherical system of coordinates with polar axis coincided with the axis of the Earth's rotation, used for numerical integration of CR trajectories in the real geomagnetic field: 1 – the CR station with coordinates λ_{st} , φ_{st} ; 2 – trajectory of particle; 3 – asymptotic direction, characterized by angles Λ , Φ

3.5 Main Methods of Numerical Calculation of Charged-Particle Trajectories

$$\begin{cases} \frac{dt_r}{ds} = 0.003R^{-1} \left(t_{\theta}H_{\varphi} - t_{\varphi}H_{\theta} \right) + \frac{t_{\theta}^2}{r} + \frac{t_{\varphi}^2}{r}, \\ \frac{dt_{\theta}}{ds} = 0.003R^{-1} \left(t_rH_{\theta} - t_{\theta}H_r \right) - \frac{t_rt_{\varphi}}{r} - \frac{t_{\theta}t_{\varphi}}{rtg\theta}, \\ \frac{dt_{\varphi}}{ds} = 0.003R^{-1} \left(t_rH_{\theta} - t_{\theta}H_r \right) - \frac{t_rt_{\varphi}}{r} - \frac{t_{\theta}t_{\varphi}}{rtg\theta}, \\ \frac{dr}{ds} = t_r, \quad \frac{d\theta}{ds} = \frac{t_{\theta}}{r}, \quad \frac{d\lambda}{ds} = \frac{t_{\varphi}}{r\sin\theta}, \end{cases}$$
(3.89)

where t_r , t_{θ} , t_{φ} are components of the unit vector tangent to the trajectory, ds is the element of trajectory length. The initial condition $r_{s=0} = r_o$, $t_{s=0} = t_o$, and the initial step h used for starting numerical integration according to Merson's modification. The initial step h was chosen according to the formula

$$h = \begin{cases} 0.1, & \text{if } \rho \le 10, \\ 0.01\rho, & \text{if } \rho > 10, \end{cases}$$
(3.90)

where ρ is the radius of the trajectory curvature

$$\rho = \left(\rho_r^2 + \rho_{\theta}^2 + \rho_{\lambda}^2\right)^{1/2}$$
(3.91)

and

$$\rho_r = \frac{\mathrm{d}t_r}{\mathrm{d}s} - \frac{t_\theta^2}{r} - \frac{t_\lambda^2}{r} = 0.003 R^{-1} \left(t_\theta H_\varphi - t_\varphi H_\theta \right), \qquad (3.92)$$

$$\rho_{\theta} = \frac{\mathrm{d}t_{\theta}}{\mathrm{d}s} - \frac{t_r t_{\theta}}{r} - \frac{t_{\lambda}^2}{r \mathrm{tg}\theta} = 0.003 R^{-1} \left(t_{\varphi} H_r - t_r H_{\varphi} \right), \qquad (3.93)$$

$$\rho_{\varphi} = \frac{\mathrm{d}t_{\varphi}}{\mathrm{d}s} + \frac{t_r t_{\varphi}}{r} + \frac{t_{\theta} t_{\varphi}}{r \mathrm{tg}\theta} = 0.003 R^{-1} \left(t_r H_{\theta} - t_{\theta} H_r \right). \tag{3.94}$$

The components of the geomagnetic field in the chosen spherical system of coordinates will be

$$H_r = -\frac{\partial U}{\partial r}, \quad H_\theta = -\frac{1}{r}\frac{\partial U}{\partial \theta}, \quad H_\varphi = -\frac{1}{r\sin\theta}\frac{\partial U}{\partial \varphi}, \quad (3.95)$$

where, for inside sources,

$$U = r_E \sum_{n=1}^{6} \left(\frac{r_E}{r}\right)^{n+1} \sum_{m=0}^{n} \left(g_n^m \cos m\varphi + h_n^m \sin m\varphi\right) \bar{P}_n^m(\cos \theta)$$
(3.96)

and

$$\bar{P}_n^m(\cos\theta) = \left(\frac{(2-\delta_{nm})(n-m)!}{(n+m)!}\right)^{1/2} P_n^m(\cos\theta), \qquad (3.97)$$

where δ_{nm} is the Kronecker symbol which is equal to 0 at $m \neq n$ and 1 at m = n.

To start the numerical integration of the system Eq. 3.89, it is necessary to choose the initial condition. Let it be determined by values r_o , θ_o , φ_o , t_{ro} , $t_{\theta o}$, $t_{\varphi o}$ (the first three determine the initial position and second three – the initial direction). The parameters of initial position are

$$r_{\rm o} = a \left(1 - \varepsilon_{\rm e}^2 \cos^2 \lambda_{\rm st}\right)^{-1/2} + 0.020, \quad \theta_{\rm o} = 90^{\rm o} - \lambda_{\rm st}, \quad \varphi_{\rm o} = \varphi_{\rm st},$$
 (3.98)

where *a* is the polar (minimal) radius of the earth, ε_e is the eccentricity of the elliptical earth, and λ_{st} and φ_{st} are the geographical latitude and longitude of the CR station. Let us remember that for the unit of length we chose 1,000 km. The initial direction of a negative particle moving from the earth is the following:

$$t_{ro} = \cos \zeta, \quad t_{\theta o} = -\sin \zeta \cos \chi, \quad t_{\varphi o} = \sin \zeta \sin \chi, \quad (3.99)$$

where ζ , χ are zenithal and azimuthal angles of the positive particle arriving at the earth surface (more exactly, at altitude 20 km). The azimuthal angle is counted from the geographical north in a clockwise direction.

In the first we calculate the three components of the magnetic field vector at the starting point according to Eqs. 3.95-3.97. Then we determine the radius of the trajectory curvature according to Eqs. 3.91–3.94, and after this we calculate the length of integration step h_1 according to Eq. 3.90. Then we can start the integration of the system of particle moving equations described by Eq. 3.89 by the Merson's modification of fourth-order Runge-Kutta method by using Eqs. 3.84-3.85; as a result we obtain the next point of the particle trajectory and by Eq. 3.86 determine the error of our calculations ε_1 . If $\varepsilon_1 \leq \varepsilon$ (where ε is the ordered error of trajectory numerical calculation), we can go to the calculation of the next point. If $\varepsilon_1 > \varepsilon$, we determine by Eq. 3.88 the necessary smaller step h (to decrease the error up to the value ε), and repeat the numerical integration of Eq. 3.89 by Merson's modification of fourth-order Runge-Kutta method by using Eqs. 3.84-3.85. So, step by step, we determine full trajectory up to the distances where the geomagnetic field has no effect. For controlling of the obtained results, we use the numerical integration of the trajectory in the inverse direction for a particle with the same rigidity, but with a positive charge (the difference in directions at starting points near the earth's surface must be smaller than 0.15° – see Section 3.5.7).

As a result of a lot of numerical integrations of CR trajectories, it was found that there are three types of trajectories:

- 1. The trajectories crossing the earth's surface
- 2. Quasi-trapped trajectories
- 3. Trajectories which are going to infinity

The trajectories of types 1 and 2 are empty because the primary CR particles arriving at the earth's surface cannot cross part of the earth and cannot be trapped. For these two types of trajectories penumbra function f(R) = 0. For type 3 trajectories, along which positive primary CR particles arrive from infinity to the earth's surface (but without crossing this surface before) penumbra function f(R) = 1. According to this

determination of types of trajectories in the real geomagnetic field, the numerical integration finishes if one of the following three conditions is fulfilled:

$$r \le r_o, \quad n = 5000, \quad r \ge 10S,$$
 (3.100)

where *n* is the number of steps and *S* is Störmer's unit of length expressed in 1,000 km. The first condition in Eq. 3.100 means that the negative particle crossed the earth's surface (i.e., the trajectory is empty); the second condition in Eq. 3.100 means that the negative particle became quasi-trapped (i.e., again, the trajectory is empty); the third condition in Eq. 3.100 means that the negative particle goes to the distance where the influence of the geomagnetic field on particle moving became negligible (i.e., the trajectory of particle goes to infinity and only in this case, penumbra function f(R) = 1). Calculations show that the limiting of computations by condition r = 10S gave an error in the asymptotic direction of not more than 0.1° . By the final values θ , φ , t_r , t_{θ} , t_{φ} of the particle position and moving direction at r = 10S it is easy to determine the asymptotic latitude

$$\Lambda = \operatorname{arctg}\left(\frac{-t_{\theta}\sin\theta + t_{r}\cos\theta}{\sqrt{t_{\varphi}^{2} + (t_{\theta}\cos\theta + t_{r}\sin\theta)^{2}}}\right),$$
(3.101)

and asymptotic longitude

$$\Phi = \varphi + \arctan\left(\frac{t_{\varphi}}{t_{\theta}\cos\theta + t_r\sin\theta}\right).$$
(3.102)

3.5.9 Divergence-Free Magnetic Field Interpolation and Symplectic Method of Charged-Particle Trajectory Integration

In Mackay et al. (2006) an interpolation method is presented for calculating a divergence-free magnetic field at arbitrary locations in space from a representation of that field on a discrete grid. This interpolation method is used along with symplectic integration to perform particle trajectory integrations with good conservation properties. These integrations are better at conserving constants of motion and adiabatic invariants than standard, described above, non-symplectic Runge–Kutta integration schemes.

The matter of the problem is that in many cases of practical interest, the electric and magnetic fields are too complex to be expressible in terms of analytic functions. In such cases, according to Mackay et al. (2006), the fields need to be calculated numerically on a discrete grid, from which their values may then be interpolated at arbitrary locations in space. Two main issues may arise when tracing particle trajectories with such fields. One has to do with whether or not the interpolated magnetic field is divergence-free. The other is related with the conservation properties of the integration scheme itself.
When integrating the full trajectory of a particle in an electric and magnetic field, it is important that the magnetic field satisfy $\nabla \times B = 0$, as this is a necessary condition for the magnetic moment to be an adiabatic invariant. Let us note that $\nabla \times \mathbf{B} = 0$ is automatically satisfied if one works with an analytic field, such as a dipole field. When working with a numerically generated field, however, the actual field values are only given at discrete grid points, and care must be taken to interpolate the field in such a way as to ensure that $\nabla \times \mathbf{B} = 0$. In general, a field calculation based on a piecewise multi-linear interpolation of the discretized field will not satisfy this condition. In the context of magneto-hydrodynamic (MHD) plasma modeling, the importance of satisfying $\nabla \times B = 0$ was pointed out by Brackbill and Barnes (1980). It was shown that failure to satisfy this condition in MHD simulation codes may lead to unphysical sources in such models. This led to the development of discretization schemes on the magnetic field that satisfied the divergence-free condition on a discrete grid (Töth, 2000). With the further use of adaptive mesh refinement in MHD codes, interpolation schemes for discretized magnetic fields, capable of producing a divergence-free field at arbitrary locations in space were also developed. For example, Balsara (2004) and Töth and Roe (2002) developed techniques for interpolating magnetic fields everywhere in space, from fields discretized on a grid, with the property that the resulting fields are analytically divergence-free. Mackay et al. (2006) note that these methods, however, generally lead to interpolated fields with discontinuities in the components parallel to cell interfaces. While adequate for MHD simulation codes (the perpendicular component of the field is continuous and smooth across cell faces), these interpolation techniques are not applicable to highorder particle integrations, as they would lead to unacceptable errors in conservation of the first adiabatic invariant *m*.

The second issue has to do with numerically preserving exact or approximate constants of the motion. If such constants exist analytically, they may not be preserved numerically, depending on the integration method used. For example, if particle trajectories are integrated using the standard Runge–Kutta scheme, it is known that errors in the total energy of the particles can grow without bounds (Yoshida, 1992; Shimada and Yoshida, 1996). An alternative to the standard explicit Runge–Kutta methods is symplectic integration (the description of this method and application for the case of dipole magnetic field are considered above, in Section 2.6). Methods based on this approach preserve the symplectic structure of the Hamiltonian; i.e., they conserve phase space density of Hamiltonian systems, thereby better preserving exact constants of the motion (Kinoshita et al., 1991).

Often, when performing particle trajectory integrations, it is necessary to use magnetic fields that have been computed at discrete grid points. One can ensure that an interpolation of this field satisfies $\nabla \times B = 0$ by working with the magnetic vector potential A and ensuring that the interpolation is C² continuous (the field and its first two derivatives are continuous in the entire domain). There are several ways of solving for A. For instance, one can directly solve the set of coupled partial differential equations from $\nabla \times A = B$, together with appropriate boundary conditions, to obtain the vector potential at prescribed grid points. In problems with symmetry, in which one of the coordinates is ignorable, it is usually possible to express the mag-

netic field in terms of stream, or flux functions (Friedberg, M1987). These, in turn, may be calculated from straightforward numerical integrations of the (divergence-free) field on a discrete grid. High-order interpolation (as provided, e.g., by cubic splines) of those flux functions and their derivatives can then be computed to yield divergence-free magnetic fields. This was the approach followed by Shimizu and Ugai (1995) who were the first to apply these techniques to azimuthally symmetric toroidal and mirror geometries.

3.5.10 Symplectic Tracing of High-Energy Charged Particles in the Inner Magnetosphere

In the considered approach of Mackay et al. (2006), the vector potential A is calculated using Fourier transforms. This is applicable to the calculation of arbitrary fields in three dimensions, and it does not rely on any symmetry in the problem. On a technical note, it is preferable, when computing the interpolation of B, to subtract the (strong) earth dipole field from the discretized field to be interpolated. This "reduced" magnetic field can then be interpolated with the technique presented below, and the earth dipole field can be added back analytically. This approach, while not necessary, has the advantage of greatly reducing interpolation errors in the vicinity of the earth, where the field is mainly dipolar. Away from the earth, the dipole field is weak, and the subtraction and addition of the dipole field has no significant impact on the interpolation error.

According to Mackay et al. (2006), writing the relation between A and B, in terms of the Fourier transformed variables, and without loss of generality, assuming $\nabla \times A = 0$ (i.e., assuming the Coulomb gauge), we readily find

$$\bar{\mathbf{A}} = \frac{i\mathbf{k} \times \bar{\mathbf{B}}}{k^2},\tag{3.103}$$

where $\bar{\mathbf{A}}$ and $\bar{\mathbf{B}}$ are, respectively, the Fourier transforms of A and B in the spatial coordinates, and k is the wave vector. In these expressions, and in what follows, the dependence of the Fourier transformed fields on the wave vector k is not written explicitly for brevity. In practice, in order to take advantage of the numerical efficiency of fast Fourier transforms, the fields and their transforms are considered on a uniform Cartesian grid, and the number of grid points in each *x*, *y*, and *z* directions is an integer power of two. If the original discretized field is provided on an unstructured grid, or on a grid that does not match our interpolation grid, it is then necessary to first use a suitable interpolation scheme to project the field on our grid. Once $\bar{\mathbf{A}}$ has been found, it is then straightforward to determine A by calculating the inverse Fourier transform. Mackay et al. (2006) note that, when solving for $\bar{\mathbf{A}}$ in Eq. 3.103, the contribution from $\bar{\mathbf{B}}$ corresponding to k = 0 is ignored. This is equivalent to subtracting the average value of *B* before taking the Fourier transform. Therefore, once A has been calculated by Eq. 3.103, the contribution from

the average magnetic field must be added back in order to obtain an expression for the full vector potential. With B_0 representing the average of B over the domain, the corresponding expression for A_0 ,

$$\mathbf{A}_0 = -(\mathbf{r} \times \mathbf{B}_0)/2, \tag{3.104}$$

is then added analytically to yield the total vector potential. It is worth emphasizing that this procedure will always produce a divergence-free field, independently of the quality of the original discretized field, or of whether it is divergent-free or not. The quality of this interpolated field, however, will only be as good as that of the original field.

Because of the periodicity implied by taking Fourier transforms in the x, y, and z coordinates, and because, in general, the discretized magnetic field is not periodic in these coordinates, a straightforward Fourier expansion of the field on a given domain would lead to approximating the given field as a periodic discontinuous function. This, in turn, would result in a slow convergence rate in the coefficients of the Fourier series. In practice, this slow convergence would manifest itself as marked Gibbs oscillations in the field in the vicinity of those discontinuities near the domain boundaries (Mathews and Walker, M1971). In order to avoid these discontinuities, and unphysical oscillations, the domain is expanded by a factor two in each spatial dimension (thus leading to an eightfold expansion of the original volume), with the extra portion being filled with reflections of the field in the original domain so as to make the extended field periodic and continuous at the boundaries.

With A being determined at each of the grid points, it can then be fitted with cubic splines. It is necessary to use cubic interpolation functions here, as opposed to lower-order interpolation functions, because of the requirement that $\nabla \times B = 0$. Indeed, this condition can only be satisfied provided that

$$\frac{\partial^2 A_j}{\partial x_j \partial x_k} = \frac{\partial^2 A_j}{\partial x_k \partial x_j},\tag{3.105}$$

i.e., provided that the interpolating function be C² continuous. The same basic technique can also be used to interpolate the scalar potential, Φ . Considering a static electric field, for simplicity, the spatial Fourier transform of $E = -\nabla \times \Phi$ leads to

$$\bar{\Phi} = \frac{\mathbf{i}\mathbf{k}\cdot\bar{\mathbf{E}}}{\mathbf{k}^2}.$$
(3.106)

Note that, as with the magnetic field, the spatial average of the electric field (the k = 0 contribution) must be excluded from this expression. With E_0 representing the volume-averaged electric field, the associated contribution to the scalar potential is given by

$$\Phi_0 = -\mathbf{r} \cdot E_0 \tag{3.107}$$

When that expression for Φ_0 is added to the inverse Fourier transform of $\overline{\Phi}$ obtained in Eq. 3.106, a complete prescription for the scalar potential is obtained, which can then be interpolated with cubic splines, as described above for the vector potential. A symplectic integration method is one that preserves the symplectic structure of a Hamiltonian system; that is, for which $dp \wedge dq = dp' \wedge dq'$. In this expression, q and p represent canonical coordinates and momenta for a given Hamiltonian. Unprimed variables refer to some initial time step t, while primed variables refer to the corresponding coordinates and momenta numerically calculated at an advanced time $t + \Delta t$. Many studies have shown the effectiveness of symplectic integration with regard to energy conservation. For example, Gladman et al. (1991), Rieben et al. (2004), and Shimada and Yoshida (1996) showed that unlike standard explicit Runge–Kutta integrators, symplectic integrators did not lead to secular growth of error in exact constants of the motion. For that reason, even though symplectic integration is more elaborate to implement, and computationally more intensive, it is the only practical technique in problems that require very long integration times.

The symplectic integration method considered by Mackay et al. (2006), is of the implicit Runge–Kutta type. Specifically, given a differential equation of the form

$$\frac{\mathrm{d}\mathbf{y}}{\mathrm{d}t} = \mathbf{F}\left(\mathbf{y}\right),\tag{3.108}$$

the s stage Runge-Kutta method is written as

$$\mathbf{y}_{n+1} = \mathbf{y}_n + h \sum_{i=1}^{s} b_i \mathbf{F}(\mathbf{Y}_i), \qquad (3.109)$$

where

$$\mathbf{Y}_{i} = \mathbf{y}_{n} + h \sum_{j=1}^{s} a_{ij} \mathbf{F}(\mathbf{Y}_{j}), \qquad (3.110)$$

It was independently shown by Lasagni (1988), Sanz-Serna (1988), and Suris (1989) that if the coefficients a_{ij} and b_i satisfy

$$b_i b_j = b_i a_{ij} + b_j a_{ji}, (3.111)$$

where no summation is implied on repeated indices, then this implicit Runge–Kutta method is symplectic. In particular, the Gauss–Legendre Runge–Kutta methods are symplectic (Sanz-Serna, 1988). For the fourth-order symplectic Runge–Kutta method, these coefficients are given as

$$(a_{ij}) = \begin{pmatrix} \frac{1}{4} & \frac{1}{4} - \frac{\sqrt{3}}{6} \\ \frac{1}{4} + \frac{\sqrt{3}}{6} & \frac{1}{4} \end{pmatrix}, \quad (b_j) = \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \end{pmatrix}.$$
 (3.112)

Because of the nonlinearity of the function F in y, the solution of this system of implicit equations must be done iteratively. In the following, Mackay et al. (2006) use a simple functional iteration technique. An initial guess is assumed for the Y_i , and this is used in equation (3.110) to find an improved estimate of Y_i . This process is repeated until the norm of the difference between two successive approximations becomes smaller than a prescribed value ε_{ik} . The convergence criterion is formulated as

3 Cosmic Rays in the Real Geomagnetic Field

$$\boldsymbol{\varepsilon} = \left| \bar{\mathbf{Y}}_{i}^{k+1} - \bar{\mathbf{Y}}_{i}^{k} \right| \le \boldsymbol{\varepsilon}_{ik}, \qquad (3.113)$$

where $\bar{\mathbf{Y}}_{i}^{k}$ is the estimate of the normalized \mathbf{Y}_{i} vector at iteration step k. In this expression, vectors $\bar{\mathbf{Y}}_{i}^{k}$ are scaled by dividing all coordinate and momentum variables of \mathbf{Y}_{i}^{k} , respectively, by a prescribed representative coordinate and momentum, so as to have all components of $\bar{\mathbf{Y}}_{i}^{k}$ of order unity. After the first two time steps, Mackay et al. (2006) use the prescription given by Calvo et al. (2003) to obtain good estimates of the starting initial guesses for Y.

A simple case which illustrates the power of the symplectic integration method is that of a proton moving in a dipole field. Here, the field that is being considered by Mackay et al. (2006) is purely analytic, thereby automatically satisfying $\nabla \times B = 0$; all that is being considered in this case is the difference between symplectic integration and the standard (explicit) Runge–Kutta method. The fourth-order symplectic Runge–Kutta integration method is used to solve Hamilton's equations resulting from the Hamiltonian for a charged particle in the earth's dipole magnetic field, namely,

$$H = \frac{1}{2m} \left[p_r^2 + \frac{p_{\theta}^2}{r^2} + \frac{1}{r^2 \sin^2 \theta} \left(p_{\phi} + \frac{q\mu_o M \sin^2 \theta}{4\pi r} \right)^2 \right],$$
 (3.114)

where r, θ , and ϕ are the usual spherical coordinates, and p_r , p_{θ} , and p_{ϕ} , are the associated canonical moments, $M = 8 \times 10^{22} \text{ Am}^2$ is the value for the earth's magnetic moment. For comparison, the standard non-symplectic fourth-order Runge–Kutta method is used to solve the equations of motion resulting from the Lorentz force acting on a charged particle in a magnetic field,

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = \frac{q}{m} \left(\mathbf{v} \times \mathbf{B} \right). \tag{3.115}$$

The initial conditions used for the particle tracing are taken from Yugo and Iyemori (2001). A single proton is initially placed with its guiding center at 5 $r_{\rm E}$ on the equatorial plane. It is given the energy of either 10 keV or 10 MeV, and a pitch angle at its initial position of 30° or 90°. Following Yugo and Iyemori (2001), the step size is taken to be 0.016 times the Larmor period at the initial position, and the particle trajectories are integrated for 10⁷ time steps. The error in the energy at each time step is calculated as

error
$$= \frac{|E - E_0|}{E_0},$$
 (3.116)

where E_0 is the exact energy of the proton, calculated at its initial position. Results for both methods are shown in Fig. 3.5. As can be seen from Fig. 3.5, the error in energy that occurs for the symplectic integration method is much smaller than that with the Runge–Kutta integration. In fact, when the pitch angle is 30°, the accumulation of error that occurs for the Runge–Kutta method is so large that $|E - E_0|/E_0$ quickly exceeds unity, and the integration is terminated. This occurs after 6,841 time



Fig. 3.5 Relative error in energy for (*top*) fourth-order explicit Runge–Kutta method and (*bottom*) fourth-order symplectic method for protons in the Earth's dipole field, initially at $5r_E$. The energies and pitch angles of the protons are **a** 10 keV and pitch 90°, **b** 10 MeV and pitch 90°, **c** 10 keV and pitch 30°, and **d** 10 MeV and pitch 30°. The error obtained with the Runge–Kutta integrator with a pitch angle of 30° increases above unity in just a few time steps, and it is not visible in panels c and d (From Mackay et al., 2006)

steps in the 10 keV case, and after only 301 time steps in the 10 MeV case. For this reason, the error from the explicit Runge–Kutta method is not visible in panels c and d of Fig. 3.5.

As was noted by Mackay et al. (2006), recently there has been interest in the trapping of charged particles in the cusp region of the magnetosphere (e.g., Sheldon et al., 1998; Chen et al., 2001). It has been suggested that this could be a major acceleration region, and that it could provide a possible explanation for particle energizing in the magnetosphere (Chen et al., 1998; Fritz and Chen, 1999; Fritz et al., 2000). Mackay et al. (2006) look at differences found in integrating trajectories of trapped protons in that region using three integration techniques. As a reference, the first one considered uses the symplectic integration technique with a magnetic field that satisfies $\nabla \times B = 0$. The second approach uses a standard (non-symplectic) Runge– Kutta integration, also with a divergence-free magnetic field. Third, Mackay et al. (2006) integrate trajectories with the same non-symplectic Runge-Kutta method, but with a magnetic field that is interpolated using a simple multi-linear formula, for which the magnetic field is, in general, not divergence-free. The results from the symplectic integration are deemed to be the most accurate, and they provide a reference for those of the other two methods. The comparison between results obtained with the Runge-Kutta integration with interpolated fields satisfying, or not, the divergence-free conditions will therefore provide a direct assessment of the importance of satisfying this condition. Finally, these example calculations are for the purpose of comparing the numerical properties of the different integration and interpolation techniques, and should not be seen as a detailed study of the physics of particle dynamics in the cusp. Another useful comparison concerns the time evolution of the energy and the first adiabatic invariant *m* computed with both approaches. The variations in these two quantities have been considered along several particle trajectories calculated with the two interpolation schemes described above. Figures 3.6 and 3.7 show representative results from two trapped particles.



Fig. 3.6 Relative error in energy calculated with fourth-order explicit Runge–Kutta integration using cubic spline interpolation with $\nabla \times B = 0$ (dotted lines) and with multi-linear interpolation of the fields ($\nabla \times B \neq 0$, solid lines). Errors are shown for two representative trapped particles (From Mackay et al., 2006)



Fig. 3.7 Time evolution of the magnetic moment calculated for two representative trapped 100 eV protons with explicit Runge–Kutta integration using cubic spline interpolation with $\nabla \times B = 0$ (dotted lines) and with multi-linear interpolation of the fields with $\nabla \times B \neq 0$ (solid lines). The two particles selected are the same as in Fig. 3.6 (From Mackay et al., 2006)

In both cases shown in Figs. 3.6 and 3.7, the particle energy is 100 eV, their initial conditions are the same for both field interpolation schemes, and both particles remain trapped during the entire 10 h simulation period. Figure 3.6 shows the error in the energy computed with both interpolated fields. In one case (panel a), the integration carried with $\nabla \times B = 0$ is seen to lead to a smaller error in the conservation of the energy, while in the other (panel b), it is the other way around. In both cases, however, energy is relatively well conserved, with the maximum relative error after 10 h being of order 10^{-5} . The lack of sensitivity on the condition $\nabla \times B = 0$, in

energy conservation is consistent with the fact that, as noted previously, the Lorentz force is perpendicular to v, and does not do any work. This is independent of whether $\nabla \times \mathbf{B} = 0$ is satisfied or not. The situation is different, however, with the first adiabatic invariant. Indeed, it is known that smoothness in the fields and $\nabla \times B = 0$ are necessary conditions for μ to be an approximate constant of the motion. This is confirmed in Fig. 3.7, which shows the evolution of μ in time, computed with and without $\nabla \times B = 0$, for the same particles as in Fig. 3.6. After an initial transient period, during which the particles go through a region of weak magnetic field (where μ is not expected to be a good invariant), the particles drift on trajectories where μ is nearly constant. After the initial transient period, however, the oscillations in μ are seen to be noticeably larger when the integration is carried with a magnetic field that does not strictly satisfy $\nabla \times B = 0$. Qualitatively, these oscillations are also generally more irregular when the integration is carried in a non-divergence-free field and the variations appear on a larger timescale. While qualitatively distinct, the differences observed here in the variations of μ are quantitatively relatively small. In the situation considered, however, where particles are weakly trapped in the cusp region, these small differences are sufficient to yield important differences in the predicted confinement over long integration periods. In Fig. 3.7 the initial magnetic moment, computed for the same particle, differs between the two methods of integration. For example, in panel a, the initial value of μ is approximately 1.7×10^{-9} when computed for the scheme in which B is not divergence-free, while, for the same initial conditions, μ is approximately 1.2×10^{-9} , when μ is not divergencefree. This is because (1) both methods use different interpolation techniques for the magnetic field, (2) the field is very weak in the region of injection, and (3) the magnetic moment is inversely proportional to B. Thus, in that case, the small absolute difference in the interpolation errors associated with the two approaches results in an appreciable difference in the initial values of μ .

Mackay et al. (2006) came to the following conclusions:

- 1. A technique for interpolating the magnetic field from numerically computed field values on a discrete grid with the Fourier transforms is used to calculate the vector potential A from the magnetic field discretized on a uniform rectangular grid.
- 2. Cubic splines are then used to interpolate A anywhere in the domain, thus providing an approximation for the field with C^2 continuity. This, in turn, is required for the computed magnetic field to be divergent-free.
- 3. This method is applied to the integration of charged-particle trajectories in the earth magnetosphere. Two integration methods are considered: a fourth-order implicit symplectic method, known for its good conservation properties of Hamiltonian systems, and a standard (explicit) Runge–Kutta integration method. The latter is used to assess the importance of interpolating the magnetic field while satisfying the condition $\nabla \times B = 0$.
- 4. It was found that the computed number of particles confined in the approximately quadrupole field of the earth cusp region is considerably smaller when the condition $\nabla \times B = 0$ is not satisfied.
- 5. As expected, the computed first adiabatic invariant μ is also found to be better conserved in magnetic fields with zero divergence. This confirms that, when-

ever integrating full particle trajectories (as opposed to solving gyro-averaged or drift-kinetic equations), it is important to use magnetic fields that satisfy the divergence-free condition.

- 6. The previous conclusion is supported by the fact that, when studying (weak) trapping in the cusp region of the magnetosphere, a large fraction of the particles that are determined as being trapped when integrated with a field that satisfies $\nabla \times B = 0$, are incorrectly predicted to be lost when their trajectories are calculated with a straightforward interpolation of B that is, in general, not divergence-free.
- 7. Failure to satisfy the $\nabla \times B = 0$ condition may lead to unphysical variations in the adiabatic invariant μ and, consequently, to erroneous physical results.
- 8. The fitting and interpolating technique considered for B and E was presented in the static field approximation. This technique, however, can readily be extended to account for time varying fields by expressing the electric field in terms of $E = -\nabla \Phi \partial A / \partial t$.

3.6 Asymptotic Directions, Impact Zones, and Acceptance Cones in the Geomagnetic Field Including the Higher Harmonics

3.6.1 Examples for Different CR Stations

The necessity to include non-dipole terms in the geomagnetic field follows from the fact that the use of dipole terms only entails errors in the asymptotic directions in the order of $10-20^{\circ}$ and more, as follows from the works by McCracken and Freon (1962), McCracken (1962), Hatton and Carswell (M1963), and others (see Section 3.5.1). As examples, Figs. 3.8 and 3.9 show the asymptotic directions





Fig. 3.9 The same as in Fig. 3.8, but for the station Churchill. Rigidities of incident particles (*from right to left*): 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.27, 1.45, 1.88, 2.20, 2.63, 3.15, 3.72, 4.37, 5.14, 6.50, 8.50, and 10.5 GV

in geographic coordinates at Deep River and Churchill for particles incident along the vertical and under an angle of 32° with the vertical from the north, south, east and west. The calculations were made according to Gill's modification (see Section 3.5.4) by using Gauss coefficients of the geomagnetic field of the epoch 1955.0, according to Finch and Leaton (1957), and shown in Section 3.5.1 (see Table 3.2).

The asymptotic cones of 11 neutron monitors for particles with rigidities from 1.0 to 5.74 GV with zenith angles $<32^{\circ}$ are shown in Fig. 3.10.

3.6.2 Classification of Stations by their Acceptance Cones

McCracken (1962) showed that, whereas at one station the particles arrive in one narrow cone only, at others they come from several cones. He concluded that there are stations which cannot lie in the second, third, etc., impact zones. The correct explanation is as follows: consider Störmer's curve of asymptotic directions of trajectories passing through the dipole center, as a function of the constant γ (see



Fig. 3.10 Asymptotic cones of 11 neutron monitors for incidence of particles with rigidity from 1.0 to $5.74 \,\text{GV}$ for zenith angles $< 32^{\circ}$. The filled circles indicate the effective direction for each detector on the assumption that the rigidity spectrum of the solar particles is exponential

Fig. 2.4). Each of the branches corresponds to a definite impact zone. Since in the actual magnetic field, just as in the dipole field, the asymptotic directions lie on the Störmer curve, any station must be in the principal impact zone as well as in the others. However, the coupling coefficients at rigidities R < 1 GV are so small that particles below this rigidity contribute a negligible amount to the counting rate of neutron monitors at sea level, even for the solar particle spectrum. Hence, stations which in the second impact zone receive radiation with rigidities below 1 GV will not record this and in this sense we may speak about stations which cannot lie in the second, third, etc., impact zones. These stations have a narrow acceptance cone for solar radiation and are, therefore, most suitable for the study of the anisotropy of galactic and solar particles. No extensive integrations are required for finding the geographic distribution of these stations. Figure 2.4 shows that all stations with $R_c < 1.1 \text{ GV}$ for $\gamma = 0.7$ will receive solar radiation only when they are lying in the principal impact zone.

Putting $\gamma = 0.7$ and $R_c = 1.1 \,\text{GV}$ in the formula

$$R_c = \frac{M_E \cos^4 \lambda'}{r_E^2 \left(\gamma + \sqrt{\gamma^2 - \cos^3 \lambda' \cos \omega}\right)^2},$$
(3.117)

or for a vertical particle arriving ($\omega = \pi/2$)

$$R_c = M_E \cos^4 \lambda' / 4\gamma^2 r_E^2, \qquad (3.118)$$

where λ' is the effective geomagnetic latitude according to Quenby and Wenk (1962), we find $\lambda' = 64^{\circ}$ or $R_{c1} = 0.54$ GV.

3.6.3 Acceptance Cones for Russian and Former Soviet Net of Stations

As mentioned above, the numerical integration of CR trajectories for Russian and the former Soviet net of stations was made in Dorman et al. (1966), Dorman and Smirnov (1966a, 1967); these results were reviewed in Dorman et al. (M1971) and in Dorman (M1974). On the basis of Eq. 3.118 with the cutoff rigidities for the actual magnetic field according to Sauer (1963), Fig. 3.11 shows the curve *I* which was drawn for the Russian stations at $R_{c1} = 0.54$ GV.

Whereas in the first two polar regions above curve 1 in Fig. 3.11, the stations can lie only in the first (principal) impact zone and receive radiation from a narrow cone, all other stations, i.e., those below curve 1, can lie in the second, third, etc., zones as well and receive radiation from a wide region. Evidently the anisotropy of solar particles and galactic CR can be best studied at stations in the intermediate zone between curves 1 and 2, which receive radiation in a narrow cone from regions close to the plane of the ecliptic. These conclusions are illustrated by Fig. 3.12, showing the integration results for some stations in different zones for particles with rigidities from 1.872 to 14.9 GV for Yakutsk and from 1 to 14.9 GV for the three high-latitude stations.

The program for integrating trajectories of charged particles in the magnetic field of the earth, represented by six spherical harmonics, was applied in Dorman et al. (1966) to determine the asymptotic directions for vertically incident particles for the former Soviet net of stations in the rigidity range from 1 to 1,000 GV. The results are listed in Table A3.1.

Dorman and Smirnov (1966a, 1967) have extended this work to determine the asymptotic directions of particles reaching 13 former Soviet stations in oblique directions by computing about 5,000 trajectories in the magnetic field of the earth represented by six spherical harmonics. They used the coefficients g_n^m and h_n^m ob-



Fig. 3.11 Classification of the former Soviet net of stations with respect to acceptance cones: A – Apatity, H – Heiss Island, T – Tikhaya Bay, Y – Yakutsk. For an explanation of curves 1 and 2 see the text



Fig. 3.12 Asymptotic directions of particles recorded by neutron monitors at some former Soviet stations

tained by Adam et al. (1964b) from spherical analysis of the geomagnetic charts drawn up by the Leningrad department of the IZMIRAN for the epoch 1960. The rigidities and incidence angles for computing the trajectories must be chosen so that they can be used conveniently in the study of CR intensity variations. The region where the source is localized can be found most accurately from the relations

$$\Phi(R) W(R) \frac{\Delta D(R)}{D(R)} \Delta R = \text{const}, \quad \Lambda(R) W(R) \frac{\Delta D(R)}{D(R)} \Delta R = \text{const}, \quad (3.119)$$

where $\Phi(R)$ and $\Lambda(R)$ are the asymptotic longitude and latitude of the trajectory, W(R) is the coupling coefficient, D(R) is the differential spectrum of the primary radiation and *R* is the rigidity of the particle.

In the numerous computations of trajectories, different series of rigidities have been used by many authors, but the most suitable selection, according to Eq. (3.119)is applied in Hatton and Carswell (M1963), and Dorman and Smirnov (1966a, 1967). The integrations have been performed in the interval from 0.85 to 350 GV. Below 0.85 GV the coupling coefficients are so small that the intensity of any secondary component at sea level is practically zero and, for rigidities above 350 GV, the influence of the geomagnetic field on the trajectories may be neglected. The zenith and azimuth angles for obliquely incident particles have been so chosen that the asymptotic directions in the actual field can easily be compared with those computed in the geomagnetic dipole field. The trajectories were computed for particles incident under angles 16° and 32° from the south, east, north, and west and for important stations also for zenith angle 48° .

3.6.4 Asymptotic Directions for the Worldwide Net of CR Stations

The asymptotic directions of particle incidence were computed by McCracken et al. (M1965) for 79 CR stations of the worldwide net. Unlike Dorman and Smirnov (1967), the coefficients g_n^m and h_n^m here were taken from the development of the field according to Finch and Leaton (1957) for the epoch 1955. The computations of McCracken et al. (M1965) were made for zenith angles 0°, 16°, and 32° for the directions of incidence of the particles from the north, south, east, and west.

3.6.5 Asymptotic Directions for Solar CR During Some Great Events

The asymptotic directions of approach in the rigidity range from 5 to 20 GV computed by Smart et al. (2000) for CR muon detectors for the maximum of the 23 February 1956 and 29 September 1989 high-energy solar CR events are illustrated in Figs. 3.13 and 3.14. Asymptotic directions of approach for selected CR neutron monitors mapped on a spherical projection of the earth were computed by Smart et al. (2000) for the solar CR events of 29 September 1989 and 19 October 1989. Results are shown in Fig. 3.15.

3.6.6 Asymptotic Directions for Several Selected CR Stations

Storini et al. (2001), using the International Geomagnetic Field model for epoch 1995.0 (IGRF 95), have made a particle access study for the Yangbajing ex-



Fig. 3.13 World map projection of the asymptotic directions of approach computed for CR muon detectors for the high-energy solar CR event of February 23, 1956 (According to Smart et al., 2000)



Fig. 3.14 The same as in Fig. 3.13 but for the solar CR event of September 29, 1989 (According to Smart et al., 2000)



Fig. 3.15 Asymptotic directions of approach computed for selected CR neutron monitors mapped on a spherical projection of the Earth. These projections are oriented on the probable interplanetary magnetic field direction for two specific solar cosmic ray events. *Left*: September 29, 1989; *Right*: October 19, 1989 (According to Smart et al., 2000)

periments located in Tibet (30° 06′ 38″ N, 90° 31′ 50″ E; 4,300 m a.s.l.; average atmospheric vertical depth 606 g/cm²). Asymptotic directions and cutoff rigidities were calculated for the 100–4.10 GV rigidity interval for the following directions: vertical and zenith angles 15° and 30° for 8 azimuthal directions: N (0°), NE (45°), E (90°), SE (135°), S (180°), SW (225°), W (270°), and NW (315°). The trajectory calculations were initiated at an altitude of 20 km above the earth's surface, using a variable step range ΔR from 0.01 GV and 0.1 GV at $R \leq 20$ GV and $\Delta R = 1$ GV for R > 20 GV. The effective cutoff rigidity for the ver-



Fig. 3.16 Effective cutoff rigidities for ARGO-YBJ location for two different zenith angles and eight azimuthal angles for the epoch 1995.0 (According to Storini et al., 2001)

tical direction was found to be 13.98 GV. Oblique directions cutoff rigidities are shown in Fig. 3.16.

In Fig. 3.17 asymptotic directions are shown for vertical and zenith angle 15° , and in Fig. 3.18 for zenith angle 30° . The maps of asymptotic directions for CR particle rigidities of 25, 30, 40, 50, 70, and 100 GV for the vertical direction and zenith angles 15° and 30° are shown in Fig. 3.19.

3.7 On the Connection of CR Cutoff Rigidities in the Real Geomagnetic Field with the *L*-Parameter of McIlwain

3.7.1 Results for Dipole Field

The classical Störmer equation determining the cutoff rigidity for vertically incident particles in the dipole field (see Chapter 2)

$$R_{\rm c} = M_{\rm E} \cos^4 \lambda / 4r_{\rm E}^2, \qquad (3.120)$$

(where $M_{\rm E}$ is the earth's magnetic moment, $r_{\rm E}$ its radius of the earth, and λ the geomagnetic latitude) may be used with McIlwain's (1961) *B–L* coordinate system for taking the effects of the eccentricity of the geomagnetic field into account (Sauer, 1963; Sauer and Ray, 1963). With the relation

$$r_{\rm E} = L\cos^2\lambda, \qquad (3.121)$$



Fig. 3.17 CR asymptotic directions for vertical and 15° zenith angle incident particles at ARGO-YBJ location (21–100 GV from *right* to *left* with the step $\Delta R = 1$ GV). The 0° latitude is shown by a dotted line, the geographic longitude of ARGO-YBJ detector is indicated by a vertical arrow (According to Storini et al., 2001)

where L is the parameter of McIlwain (1961) for the real geomagnetic field, the values of the cutoff rigidities of CR can be represented in the form

$$R_{\rm c} \approx M_{\rm E}/4L^2 \approx 14.9L^{-2}\,{\rm GV}.$$
 (3.122)

3.7.2 Results for Trajectory Calculations for Quiet Time

Comparison of the cutoff rigidities computed from Eq. 3.122 with the results of trajectory computations by Ray (1963b, c; 1965) showed that the relative difference lies between -11% and +8%. Lin et al. (1963) showed that at high latitudes a close relation between the cutoff rigidities at the earth's surface and the values of the *L*-coordinate exists, but at lower latitudes the lines of constant *L* and of constant cutoff rigidity begin to deviate considerably from each other.

Smart and Shea (1965) instead of using Eq. 3.122 proposed the expression

$$R_c = K L^{-\gamma} \text{GV}, \qquad (3.123)$$



Fig. 3.18 The same as in Fig. 3.17, but for zenith angle 30° (From Storini et al., 2001)

where *K* and γ are obtained by the least-squares method from the values of cutoff rigidities for vertically incident particles. They found that the computed effective cutoff rigidities agree well with Eq. 3.123, if K = 15.89 and $\gamma = 1.995$. A later, more detailed correlation analysis based on Eq. 3.123 by Smart and Shea (1967), showed that the planetary distribution of R_c , except within 2° from the CR equator, is best represented by K = 16.59, $\gamma = 2.083$ for the cutoff rigidities from Quenby and Wenk (1962); the standard deviation with respect to Eq. 3.123 then is 8.2%, for 3,706 values of R_c . The cutoff rigidities from Makino (1963) give K = 15.99, $\gamma = 2.014$, the standard deviation for 916 values of R_c being 20.1%. Finally, for the trajectory computations by Shea et al. (1965a, b), K = 15.96 and $\gamma = 2.005$, with standard deviation 5.7% for 226 values of cutoff rigidity. Figure 3.20 illustrates these comparisons.

A more accurate study of the relation between cutoff rigidities and the *L*-coordinates was made by Dorman and Smirnov (1966b). The real geomagnetic field has no axial symmetry, but, as shown by Quenby and Webber (1959) the influence of the asymmetric part of the field on cutoff rigidity is small and may be neglected. Considering that the geomagnetic potential may be represented by an infinite sum of spherical harmonics and, neglecting the part of the field depending on longitude, we find for the field in the equatorial plane



Fig. 3.19 Sky map of the asymptotic directions of approaching CR particles to the Yangbajing location. The cardinal directions: N, NE, E, SE, S, SW, W, and NW were considered for particle rigidities of 25, 30, 40, 50, 70, and 100 GV and zenith angles: 15° (*bottom*) and 30° and vertical (*top*) (According to Storini et al., 2001)

$$H = \sum_{n=1}^{\infty} M_n r^{-(n+2)}, \qquad (3.124)$$

and the vector potential of such a field is given by

$$\mathbf{A} = \sum_{n=1}^{\infty} \frac{M_n}{n r^{n+1}} \mathbf{e}_{\varphi}, \qquad (3.125)$$

where M_n is the moment of the *n*th harmonic of the field, and \mathbf{e}_{φ} is the unit azimuthally vector. With the magnetic field and vector potential found from Eqs. 3.124



Fig. 3.20 Relation between the *L* parameter and the calculated values of cutoff rigidities from Quenby and Wenk (1962), Makino (1963), and trajectory derived by Shea et al. (1965a, b) (According to Smart and Shea, 1967)

and 3.125 the cutoff rigidity may be found numerically, using Störmer's integral for axially symmetric fields. The cutoff rigidity of vertically incident particles for an arbitrary axially symmetric magnetic field is determined by a system of three algebraic equations (Asaulenko et al., 1965):

$$R_{c} = r_{\rm tr} H(r_{\rm tr}, 0), \quad r_{\rm tr} + R_{\rm c}^{-1} r_{\rm tr} A_{\phi}(r_{\rm tr}, 0) = \gamma, \quad A_{\phi}(r_{\rm e}, \lambda) R_{\rm c}^{-1} r_{\rm E} \cos \lambda = \gamma$$
(3.126)

with three unknowns: R_c is the cutoff rigidity, γ is Störmer's constant, r_{tr} is the distance from the center of the earth to the point of transition dividing the permitted inner and outer regions. Further, A_{φ} is the azimuthally component of the vector potential, λ is the latitude of the point of observation. Usually only six terms are included in the development of the geomagnetic field because of the finite accuracy of the geomagnetic charts. However, even when only six terms are used in the series described by Eqs. 3.124 and 3.125, substitution of the finite sums for field and vector potential leads to a system of algebraic equations of the seventh degree, the roots of which cannot be expressed in closed form. Instead, we may find an approximate solution of system Eq. 3.126 by making use of the fact that the main part of the geomagnetic field is the dipole term, considering the higher harmonics as perturbations.

On the other hand, in the dipole field the critical transition point is known to lie at a distance of one Störmer unit from the center of the dipole, and the equatorial distance of the line of force along which the particle is moving is half as large. Thus, if the transition center of the particle moves along a line of force with equatorial distance *L* earth's radii, the critical transition point lies at a distance 2*L*. When the perturbing field is superposed on the dipole field the critical point is displaced over a small distance Δr . Then, instead of Eq. 3.126, we obtain

$$\begin{cases} R_c = (2L + \Delta r) H (2L + \Delta r), \\ (2L + \Delta r) \left[1 + R_c^{-1} A_{\varphi} (2L + \Delta r, 0) \right] = 2\gamma, \\ A_{\varphi} (1, \lambda) R_c^{-1} \cos \lambda = 2\gamma. \end{cases}$$
(3.127)

Substituting the magnetic field and the vector potential determined by Eqs. 3.124 and 3.125 into Eq. 3.127 and developing each term of the sum in a Taylor series in powers of Δr , we find for R_c , when only the first terms of the developments are included,

$$R_c = [0.25 M_1 L^{-2} + 0.19 M_2 L^{-3} + 0.15 M_3 L^{-4} + 0.12 M_4 L^{-5} + 0.10 M_5 L^{-6} + 0.08 M_6 L^{-7}] \times 3 \times 10^{-7} \text{ GV.}$$
(3.128)

Here M_1, M_2, \ldots, M_6 are the magnetic moments in the harmonic development of the geomagnetic field (in units Gs cm³, Gs cm⁴, ..., Gs cm⁸, respectively), *L* is the McIlwain's parameter (in cm). Expressing each of the magnetic moments of the higher harmonics of the magnetic field by means of the non-dipole part of the field at the Equator ΔH at the longitude of the point of observation, we find, from Eq. 3.128, the following formula, which is more convenient in practice:

$$R_c = 14.9L^{-2} + \Delta H \left(18.4L^{-3} + 8.1L^{-4} + 3.1L^{-5} + 0.8L^{-6} + 0.3L^{-7} \right) \text{GV}.$$
(3.129)

Values *L* (here they are in the earth's radii r_E) as well as ΔH (in Gs) can be easily found from the charts. For L > 2.5 the second and following terms of this series can be neglected and then the cutoff rigidity is determined within 1% by Eq. 3.122. Even in the equatorial region the results given by Eq. 3.129 are not so bad, as may be seen from the satisfactory agreement shown in Fig. 3.21.



Fig. 3.21 CR equator. Full curve: measured; dotted curve: computed from Eq. 3.129

3.7.3 Using the Relation between R_c and McIlwain L-Parameter for Estimation of R_c Variations during Disturbed Periods

Rodger et al. (2006) note that the geomagnetic rigidity cutoffs are well organized in terms of the McIlwain *L*-parameter (see Sections 3.7.1 and 3.7.2, and later developments in Smart and Shea, 1994; Selesnick et al., 1995). The *L*-variation of the geomagnetic rigidity cutoff has been determined for quiet times from about 10,000 nuclei observations made by the MAST instrument on the SAMPEX satellite (Ogliore et al., 2001). These authors report that the geomagnetic rigidity cutoffs, R_c , for quiet times are given by

$$R_c = 15.062L^{-2} - 0.363 \,[\text{GV}],\tag{3.130}$$

representing average conditions for $K_p = 2.3$. As noted above, dynamic vertical cutoff rigidities dependent upon magnetic activity levels, have been determined by particle tracing (Smart and Shea, 2003) using the K_p -dependent Tsyganenko (1989) magnetospheric field model. These authors have reported that the change of proton cutoff energy with K_p is relatively uniform over the range of the original Tsyganenko (1989) model ($K_p < 5$), but the cutoff changes introduced by the Boberg et al. (1995) extension to higher K_p is non-linear such that there are large changes in proton cutoff energy for a given L value at large K_p values. Rodger et al. (2006) make use of the K_p -dependent variations in the effective vertical cutoff energies at a given IGRF L value at 450 km altitude determined from this modeling (Smart et al., 2003), but with a slight modification to ensure that the geomagnetic rigidity cutoff varies as 15.062 L^{-2} , as was observed in the SAMPEX experimental data. The results are presented in Fig. 3.22.

From Fig. 3.22 it can be seen that the change in cutoff energy with geomagnetic activity is strongly non-linear at the highest disturbance levels. Rodger et al. (2006) noted that the plot of effective vertical cutoff energies against geomagnetic latitude varying with geomagnetic activity (Fig. 3.22) is useful for summarizing the response of the geomagnetic field during geomagnetic storms.

3.7.4 Estimation of R_c for Any Altitude on the Basis of the Relationship Between R_c and L

In order to interpolate down to lower altitudes (e.g., 100 km), Rodger et al. (2006) followed the approach outlined by Smart and Shea (2003) again using the IGRF-determined *L* value. This exploits the basic relationship between R_c and *L*, i.e.,

$$R_c = C_k L^{-2}, (3.131)$$



Fig. 3.22 Variation with geomagnetic activity of the effective vertical cutoff energies for protons at an altitude of 450 km based on the modeling of Smart et al. (2003) and SAMPEX observations (Ogliore et al., 2001) (From Rodger et al., 2006)

where C_k is an altitude-independent constant. Thus, by knowing the value of C_k for the IGRF *L* value at 450 km altitude above a given location, one can determine R_c at 100 km once one knows the *L* value for that location at 100 km altitude.

3.7.5 Global Rigidity Cutoff Maps Based on the Relation Between R_c and L

Figure 3.23 presents maps of the proton geomagnetic rigidity cutoff energies for the southern (left) and northern (right) hemispheres at very low ($K_p = 0$), middle ($K_p = 4$), and high ($K_p = 9$) disturbance levels, based on the relation between R_c and *L* discussed in Sections 3.7.3 and 3.7.4. In Fig. 3.23 contour lines with units of MeV mark the geographic locations of the rigidity cutoff energies at 100 km altitude. Note that the location of the cutoffs for $K_p = 0$ and $K_p = 4$ are simply projected from Fig. 3.22 and thus are based on the Tsyganenko (1989) magnetic field model.

During geomagnetic storms, solar energetic particles (SEPs) impact larger regions of the polar atmosphere. The contour line in Fig. 3.23 showing the cutoff location for an energy of 0.001 MeV, is indicative of the "no-cutoff" region; essentially all SEPs will access the upper atmosphere located poleward of this line, irrespective of the particle energy. As shown in Fig. 3.23, the size of the "no-cutoff" region expands significantly equatorward with an increase in geomagnetic activity.

3 Cosmic Rays in the Real Geomagnetic Field Proton cutoff energies at 100 km altitude: Kp = 0





Proton cutoff energies at 100 km altitude: Kp = 4



Proton cutoff energies at 100 km altitude: Kp = 9

Proton cutoff energies at 100 km altitude: Kp = 4



Proton cutoff energies at 100 km altitude: Kp = 9



Fig. 3.23 Contour plots showing the locations of the rigidity energy cutoffs at 100 km. The contour labels have units of MeV, and the location Halley is shown with a square. Note that as the geomagnetic activity levels increase, the cutoffs move equatorward (From Rodger et al., 2006)

The basic shape of the SEP, the affected region predicted by Fig. 3.23, is rather similar to the zone of high ozone losses observed by satellite measurements during an SEP event (Seppälä et al., 2004; for details see in Chapter 13 of Dorman, M2004).

3.7.6 Calculations of R_c and L for Different Models: Comparison

Rodger et al. (2006) note that the Tsyganenko (1989, 1996) geomagnetic field models are among a small set of external field models, which are commonly used as standard tools. However, it is less widely appreciated that, at highly disturbed geomagnetic conditions, all geomagnetic field models struggle to reproduce the experimentally observed fields (see Fig. 3.24).

Figure 3.24 shows the L value of Halley calculated using various field models during the 4 November 2001 SEP event, to be contrasted against the IGRF and Tsyganenko (1989) magnetic field models which are the basis of the rigidity cutoff energy predictions.

The additional L value calculations shown in Fig. 3.24 were undertaken using the European Space Agency's Space Environment Information System (SPEN-VIS), taking as input 3-hourly geophysical parameters (geomagnetic indices, solar wind, and IMF measurements) provided by the NSSDC OMNI Web databases. The 3-hour timescale is to provide "like-with-like" comparison with the



Fig. 3.24 Comparison of the McIlwain *L* value determined by various geomagnetic field models. The IGRF internal field (dotted) and the K_p -dependent Tsyganenko (1989) model (solid lines) are contrasted against a number of other models (From Rodger et al., 2006)

 K_p -driven Tsyganenko-89 (Tsyganenko, 1989) model. Figure 3.24 includes the Ostapenko-Maltsev (Ostapenko and Maltsev, 1997), Olson-Pfitzer dynamic (Pfitzer et al., 1988), Tsyganenko-96 (Tsyganenko, 1996), and "paraboloid" magnetic field models, the last of which has been proposed as ISO standard for the earth's magnetospheric magnetic field and has been developed jointly by research teams from the Skobeltsyn Institute of Nuclear Physics (Moscow) and the US Geological Survey as described in SPENVIS. Note that there is a large data gap in Fig. 3.24, covering the hours 51-75. This is due to a gap in solar wind/IMF measurements, required as inputs for all the additional magnetic field models. This gap starts just after the beginning of the peak disturbance as measured by K_p (hours 48–54). It is instructive to consider the wide variation in L values reported for Halley by the differing magnetic field models during the 4-7 November 2001 storm period (Fig. 3.24). Rodger et al. (2006) argued that the IRIS absorption measurements indicate that the geomagnetic field is not as stretched at high K_p as suggested by the Tsyganenko-89 field model and that while Halley should effectively move poleward in L value during this period, the shift should be reasonably slight. From the observed absorption levels it appears that at the peak storm time of 4-7 November 2001, the geomagnetic field was distorted such that Halley moved poleward only by about $\Delta L = 1$. The Tsyganenko-89 model suggests that the L value of Halley is shifted to $L \approx 6.5$ (i.e., $\Delta L \approx 2$). The rigidity cutoff energy of $\approx 18 \,\text{MeV}$ for highly disturbed conditions is consistent with an IGRF L shell of $L = 5.5 \ (\approx 3.5^{\circ} \text{ poleward of Hal-}$ ley) during low-disturbance conditions (e.g., $K_p \approx 1$). However, Fig. 3.24 indicates that the Tsyganenko-89 model is relatively conservative when contrasted with the Tsyganenko-96 and Olson-Pfitzer dynamic calculations, which lead to much larger poleward shifts ($\Delta L > 6$ and $\Delta L \approx 4$, respectively), and very low values of rigidity cutoff energy. In contrast, the Ostapenko-Maltsev and paraboloid magnetic field models report smaller shifts in L value during these storm conditions, both reaching $L \approx 5.5$ around the time of the highest K_p values, and thus a rigidity cutoff energy of about 18 MeV as determined above. Although further tests would be valuable, it appears that these dynamic magnetic field models would be good candidates for future work into time-varying rigidity cutoff energies, following the approach of Smart and Shea (2003).

3.8 Planetary Distribution of Cutoff Rigidities at Altitude 20 km

3.8.1 Offset Dipole and CR Cutoff Rigidity Coordinates

Smart and Shea (1995) show that coordinates based on the offset dipole are sufficiently different from the coordinates based on CR cutoff rigidity contours. The offset dipole coordinates can be determined according to Akasofu and Chapman (M1972), and Roederer (1972) by the Schmidt normalized Gauss coefficients (used for describing the earth's magnetic field) in the following way. The tilt angle θ and dipole phase angle φ will be determined as

$$\theta = \arctan\left(\left(\left(g_{1}^{1}\right)^{2} + \left(h_{1}^{1}\right)^{2}\right)^{1/2} / g_{0}^{1}\right), \qquad \varphi = \arctan\left(h_{1}^{1} / g_{1}^{1}\right), \qquad (3.132)$$

and the dipole position from the geocenter will be determined as

$$x_{ed} = \left(L_2 - g_1^1 L_5\right) / 3L_4^2, y_{ed} = \left(L_3 - h_1^1 L_5\right) / 3L_4^2, \quad z_{ed} = \left(L_1 - g_1^0 L_5\right) / 3L_4^2,$$
(3.133)

where

$$L_{1} = 2g_{1}^{0}g_{2}^{0} + \sqrt{3} \left(g_{1}^{1}g_{2}^{1} + h_{1}^{1}h_{2}^{1} \right), \quad L_{2} = -g_{1}^{1}g_{2}^{0} + \sqrt{3} \left(g_{1}^{0}g_{2}^{1} + g_{1}^{1}g_{2}^{2} + h_{1}^{1}h_{2}^{2} \right),$$

$$L_{3} = -h_{1}^{1}h_{2}^{0} + \sqrt{3} \left(g_{1}^{0}h_{2}^{1} + h_{1}^{1}g_{2}^{2} + g_{1}^{1}h_{2}^{2} \right), \quad L_{4} = \left(\left(g_{1}^{0}g_{1}^{1} \right)^{2} + \left(h_{1}^{1} \right)^{2} \right)^{1/2},$$

$$L_{5} = \left(L_{1}g_{1}^{0} + L_{2}g_{1}^{1} + L_{2}h_{1}^{1} \right) / 4 \left(\left(g_{1}^{0}g_{1}^{1} \right)^{2} + \left(h_{1}^{1} \right)^{2} \right).$$

(3.134)

On the basis of Eqs. 3.132–3.134 for epoch 1980.0 magnetic field DGRF (1992) model, Smart and Shea (1995) found that

$$\theta = 11.2^{\circ}, \quad \varphi = 289.2^{\circ}, \quad x_{ed} = 0.0605r_E, \quad y_{ed} = 0.0388r_E, \quad z_{ed} = 0.0267r_E,$$
(3.135)

where $r_{\rm E}$ is the radius of the earth. By the Störmer expression for the vertical cutoff rigidity (see Chapter 2 and details in Smart and Shea, 1977) the cutoff rigidity contours at the "top" of the atmosphere (altitude 20 km over geoids surface), can be found corresponding to the location of geomagnetic dipole described by Eq. 3.135. Results are shown in Fig. 3.25.



Fig. 3.25 The vertical cutoff rigidity contours in the offset dipole approximation found by applying the Störmer equation to the position of the magnetic dipole at the epoch 1980.0 (described by Eqs. 3.132–3.134) (According to Smart and Shea, 1995)



Fig. 3.26 The CR vertical cutoff rigidity contours determined by the trajectory-tracing on the basis of magnetic field model DGRF (1992) for epoch 1980.0, based on $5^{\circ} \times 5^{\circ}$ world grid (According to Smart and Shea, 1995)

The results in Fig. 3.25 can be compared with the vertical cutoff rigidities contours derived from CR trajectory tracing for the same epoch 1980.0 with the same model DGRF (1992). The results are shown in Fig. 3.26.

The longitudinal phase shift (which can be easily seen from comparison of Figs. 3.25 and 3.26) is about the same as that observed for the shift in the East direction for about 3 h of CR equator relative to geomagnetic equator (see Fig. 2.7).

3.8.2 CR Vertical Cutoff Rigidity Planetary Distribution for the Epoch 1955.0

Trajectory computations (up to 25 earth radii) of the penumbra for vertical incidence, with the approximation of the geomagnetic field by six harmonics according to Finch and Leaton (1957) for the epoch 1955.0, were used by Shea (1963) for many points along the course of the ship *Soya* from Japan to Antarctica and airplane expeditions from Paris to the Canary Islands. Kondo et al. (1963) compared the CR cutoff rigidities R_{c1} found by direct trajectory computations with R_{c2} computed by Quenby and Wenk (1962). They found that the relative difference $(R_{c1} - R_{c2})/R_{c1}$ for nearly 100 points along the courses of the latitude expeditions of the ships *Soya, Labrador, Atka*, and *Arnev* had a mean-square value of about 10%. The planetary distribution of the vertical cutoff rigidities was also determined by Kondo and Kodama (1965). The trajectories were computed numerically for Finch and Leaton's (1957) development of the geomagnetic field for the epoch 1955.0. The effective cutoff rigidities R_c were determined from the relation

$$\int_{R_c}^{\infty} m_i(R) D(R) \, \mathrm{d}R = \int_{0}^{\infty} f(R) \, m_i(R) D(R) \, \mathrm{d}R, \qquad (3.136)$$

where $m_i(R)$ is the integral multiplicity, and D(R) is the primary CR spectrum, and $m_i(R)D(R)$ is the sensitivity function for the *i*th component. Here f(R) takes the role of the penumbra into account; it is equal to 1 for allowed and 0 for forbidden trajectories. If $m_i(R)D(R)$ is put equal to 1, then the error in the R_c determination introduced by this approximation becomes about 0.2–0.4 GV. The interval used was 0.1 GV. Comparison with results of Shea (1963), where the interval 0.01 GV was used, showed that the errors arising on this account are on an average of about 0.08 GV (with a maximum error of 0.25 GV). Figure 3.27 shows the results.

Shea et al. (1968) calculated $5^{\circ} \times 15^{\circ}$ world grids of trajectory-derived vertical cutoff rigidities for epoch 1955.0. In these calculations, the approximation of the geomagnetic field by six harmonics according to Finch and Leaton (1957) for the epoch 1955.0 it was utilized. Results are shown in Table A3.2.



Fig. 3.27 Contours of constant threshold rigidity plotted in geographic coordinates for the epoch 1955.0 (According to Kondo and Kodama, 1965)

3.8.3 CR Vertical Cutoff Rigidity Planetary Distributions for Epochs 1965.0 and 1975.0

Shea and Smart (1975b) calculated $5^{\circ} \times 15^{\circ}$ world grids of trajectory-derived vertical cutoff rigidities for epochs 1965.0 and 1975.0. In these calculations the International Geomagnetic Reference Field according to IAGA Commission 2 (1969) was used with time derivatives applied also for epoch 1975.0. Results are shown in Table A3.3 for the epoch 1965.0 and Table A3.4 for 1975.0. The effective vertical cutoff rigidities were calculated by using penumbra functions found in Shea and Smart (1975b) for each point as described in Dorman et al. (M1972) and in Section 3.10.

3.8.4 The Change of CR Vertical Cutoff Rigidity Planetary Distribution During 20 Years, from 1955 to 1975

Table A3.5 shows the planetary distribution of the differences of CR effective vertical cutoff rigidities in 1955 and 1975.

From Table A3.5 it can be seen that, whereas minor changes ($\leq 0.2 \,\text{GV}$) in the cutoff rigidities occur in many areas of the world over this 20-year interval, major changes (>0.60 \text{GV}) occur in the Central and Southern Atlantic Ocean area and over the Central and South American land masses. Shea and Smart (1975b) came to the conclusion that while the changes in the southern hemisphere primarily decrease in the vertical cutoff rigidities, there is an area in the northern hemisphere, principally in the Atlantic Ocean, where comparable increases in the vertical cutoff rigidities are calculated.

3.8.5 CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 1980

Shea and Smart (1983) calculated $5^{\circ} \times 15^{\circ}$ world grid of trajectory-derived vertical cutoff rigidities for the epoch 1980.0. Results are shown in Table A3.6.

3.8.6 CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 1990.0

Smart and Shea (1997a) calculated $5^{\circ} \times 15^{\circ}$ world grid of trajectory-derived vertical cutoff rigidities for the epoch 1990.0. Results are shown in Table A3.7 and in Fig. 3.28.



Fig. 3.28 Contours of constant threshold rigidity plotted in geographic coordinates for the epoch 1990.0 (According to Smart and Shea, 1997a)

3.8.7 CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 1995.0

Smart and Shea (2007a) calculated $5^{\circ} \times 15^{\circ}$ world grid of trajectory-derived vertical cutoff rigidities for the epoch 1995.0. Results are shown in Table A3.8.

3.8.8 CR Vertical Cutoff Rigidity Planetary Distribution for Epoch 2000.0

Smart and Shea (2007b) calculated $5^{\circ} \times 30^{\circ}$ world grid of trajectory-derived vertical cutoff rigidities for the epoch 2000.0. Results are shown in Fig. 3.29 and in Table A3.9.

3.9 CR Effective Cutoff Rigidity Planetary Distribution for Satellite Altitudes

Smart and Shea (1997b) have derived a $5^{\circ} \times 15^{\circ}$ world grid of CR cutoff rigidities for satellite altitude at 450 km for the epoch 1990.0 employing the Definitive International Geomagnetic Reference Field for this epoch (IGRF 1991 Revision, 1992). The CR trajectory calculations were initiated in the vertical and west direction at



Fig. 3.29 Contours for vertical geomagnetic cutoff rigidities for the epoch 2000 (From Smart and Shea, 2007b)



Fig. 3.30 Contours of constant effective vertical cutoff rigidity plotted in geographic coordinates for the epoch 1990.0 at an altitude of 450 km (From Smart and Shea, 1997b)

zenith angle 90° from a distance of 6,821.2 km from the geocenter (i.e., 450 km altitude above the average earth of 6,371.2 km radius). Figure 3.30 and Table A3.10 show the results for CR vertical effective cutoff rigidity planetary distribution.

Results for planetary distribution of CR effective cutoff rigidity for the west direction at 90° zenith angle are shown in Table A3.11 and Fig. 3.31.



Fig. 3.31 Contours of constant effective cutoff rigidity for the west direction at 90° zenith angle plotted in geographic coordinates for the epoch 1990.0 at an altitude of 450 km (According to Smart and Shea, 1997b)

3.10 Cutoff Rigidities for the Worldwide Network of CR Stations

3.10.1 Calculations of Cutoff Rigidities for CR Stations and Checking by Data on CR Variations

It should be stressed once more that fully reliable values of the CR cutoff rigidities can be found only by direct numerical integration of particle trajectories in the real field of the earth, where all geomagnetic effects are automatically taken into account. This is particularly clear from the results of McCracken and Freon (1962) and Freon and McCracken (1962) who found in this way a cutoff rigidity of 1.27–1.30 GV for Port aux Francais (Kerguelen Island), which was 0.45 GV smaller than the generally adopted value. Kodama (1965) determined the cutoff rigidity for vertical incidence of 85 CR stations by straight computation of the trajectories. For rigidities between 5 and 13 GV, the computing error is ± 0.05 GV, for larger and smaller rigidities it is ± 0.1 GV. The quality of the computed threshold rigidities was estimated by comparison with data about the Forbush decreases in July 1959 and about the CR increases of 23 February 1956 and 12 November 1960. The latitude variations of these effects showed that the observed values agree better with the computations of Kodama (1965) than with those of Quenby and Wenk (1962).

3.10.2 Comparison of Different Models of Calculation

Comparing the relative merits of the various models for computing the vertical cutoff rigidities, Kenney et al. (1965) found that (1) of all models considered, the simple dipole is least satisfactory; (2) the model of Quenby and Wenk (1962) for moderate latitudes is an improvement over that of Ouenby and Webber (1959); (3) Makino's model (Makino, 1963) is only a little better than that of Quenby and Wenk (1962); and (4) the models based on McIlwain's parameter L (see Section 3.7) is sufficiently good for all regions except the equatorial ones. Three series of measurements of the position of the CR equator near South America agree well with accurate trajectory computations but not with data about the position of the equator based on the parameter L, if the simple Eq. 3.122 is used, even when the dipole is taken to be shifted to the east. To this conclusion we should add that the more accurate Eq. 3.129, derived by Dorman and Smirnov (1966b), correctly represents the observed position of the CR equator. Hence, the most accurate results for the cutoff rigidities are obtained by direct trajectory computations. In this respect, the results of Shea and Smart (1966a, b, 1967), Shea et al. (1965b, 1968), Smart and Shea (1966), McCracken et al. (M1965), and Daniel and Stephens (1966) are important; here the real magnetic field is taken into account up to six harmonics. In particular, in Smart and Shea (1966), a network of vertical R_c is given over the earth, with 15° intervals in latitude and longitude; for taking account of the penumbra effect, the computations were made with an interval of 0.01 GV. For the intermediate points, the value of R_c may be obtained by interpolation, using the L parameter. In Shea et al. (1965) R_c is determined for more than 300 points on the earth's surface, 26 points being chosen near the South African magnetic anomaly and six in the region of the Northern Atlantic, for which regions anomalous values were observed. For the regions near South Africa, the Southern Atlantic, and the Canary Islands the rigidity thresholds are found to differ by more than 15% from those computed by Quenby and Wenk (1962). It is found that with the cutoff rigidities of this work, the results for the various CR latitude measurements agree well with each other. Shea et al. (1965b) concluded that, though for a large part of the earth the cutoff rigidities computed with different models of the geomagnetic field practically do not differ from each other, for some regions this difference proves to be important in the analysis of CR effects. In Shea and Smart (1966b, 1967) values of R_c were determined by the same method for more than 100 points on the earth and it was shown that numerous observations of CR geomagnetic effects and the CR equator agree well, within the error limits, with trajectory computations of cutoff rigidity. This check gives a serious reason to consider the cutoff rigidities for the worldwide net of CR stations by McCracken et al. (M1965) as the most accurate values of R_c now available. In McCracken et al. (M1965), the trajectories were integrated with inclusion of six harmonics of the field in the range $1 r_E < r < 3.5 r_E$, five harmonics for $3.5r_{\rm E} < r < 4.0r_{\rm E}$, four harmonics for $4.0r_{\rm E} < r < 6.4r_{\rm E}$, three harmonics for $6.4r_{\rm E} < r < 11r_{\rm E}$ and the first two harmonics in the range of variation of the distance from the earth's center $11 r_{\rm E} < r < 51 r_{\rm E}$, where $r_{\rm E}$ is the radius of the earth. These computations were made for an altitude of 20 km above the earth's surface because the influence of the geomagnetic field on primary CR particles only was considered, and the first interaction of these with the nuclei of air atoms takes place at about this altitude.

3.10.3 Comparison of Different Models of the Geomagnetic Field

How do the vertical cutoff rigidities for CR stations determined by the trajectorytracing technique depend upon the geomagnetic field model utilized? To solve this important problem, Shea and Smart (1975a) calculated effective vertical cutoff rigidities for 43 CR stations by the trajectory-tracing technique for the epoch 1955 using different geomagnetic field models: Finch and Leaton (1957) and IGRF developed by IAGA Commission 2 (1969). Results are shown in Table 3.3.

From Table 3.3 it can be seen that the difference between effective vertical cutoff rigidities for two geomagnetic models lies in the interval from $+0.21 \,\text{GV}$ to $-0.08 \,\text{GV}$ (the average difference is $+0.045 \,\text{GV}$). Shea and Smart (1975a) came to the conclusion that effective vertical cutoff rigidities for the worldwide network of CR stations are essentially the same when calculated using comparable field models for the same epoch.

3.10.4 Cutoff Rigidities for Inclined Directions

Unfortunately, all results described above for R_c refer only to vertically incident particles, whereas actual time variations have been also studied for inclined components. Therefore, it is important to extend the trajectory computations of R_c to incidences under various zenith and azimuth angles. To the end of the 1960s this had been done only for the station Hyderabad (India, 17.6°N, 78.5°E). For this station, Daniel and Stephens (1966) determined R_c by trajectory computations for zenith angles 0–80° and azimuth angles 0–350°, with intervals of 10°, the first six harmonics of the actual field being included.

3.11 The CR Penumbral Effects in the Real Geomagnetic Field

3.11.1 The CR Penumbra in Dependence of Delineated Value

The penumbra effects in the dipole approximation were considered in Chapter 2 (Sections 2.4 and 2.5). For determining penumbra effects in the real geomagnetic field, it is necessary to make a lot of trajectory-traced numerical calculations. The first question is: What delineated value must be chosen? Figure 3.32 shows Smart
Station name	Geographic coordinates		Effective vertical cutoff rigidities (GV)	
	Latitude	Longitude	F&L Field	IGRF
1	2	3	4	5
Ahmedabad, India	23.01	72.61	15.94	15.82
Alma Ata, Kazakhstan	43.20	76.94	6.73	6.61
Athens, Greece	37.97	23.72	8.70	8.66
Bergen, Norway	60.40	5.32	1.14	1.13
Brisbane, Australia	-27.50	153.01	7.21	7.25
Buenos Aires, Argentina	-34.58	301.50	10.63	10.58
Chacaltaya, Bolivia	-16.31	291.85	13.10	13.07
Chicago, USA	41.83	272.33	1.72	1.69
Climax, USA	39.37	253.82	3.03	3.01
Dacca, Bangladesh	23.70	90.37	16.22	16.05
Dallas, USA	32.78	263.20	4.35	4.37
Deep River, Canada	46.10	282.50	1.02	1.02
Durham, USA	43.10	289.16	1.41	1.39
Gif Sur Yvette, France	48.68	2.13	3.61	3.55
Hafelekar, Austria	47.32	11.37	4.37	4.30
Hermanus, South Africa	-34.42	19.22	4.90	4.82
Huancayo, Peru	-12.05	284.67	13.45	13.44
Irkutsk, Russia	52.47	104.03	3.66	3.58
Jungfraujoch, Switzerland	46.55	7.98	4.48	4.45
Kerguelen Island	-49.35	70.22	1.19	1.22
Kiel, FRG	54.33	10.13	2.29	2.27
Kula, USA	20.73	203.67	13.30	13.23
Leeds, England	53.82	358.45	2.20	2.11
Lomnicky Stit, Slovakia	49.20	20.22	4.00	3.96
Makerere, Uganda	0.33	32.56	14.98	15.06
Mexico City, Mexico	19.33	260.82	9.53	9.46
Mina Aguilar, Argentina	-23.10	294.30	12.51	12.46
Moscow, Russia	55.47	37.32	2.46	2.42
Mt. Norikura, Japan	36.12	137.56	11.39	11.18
Mt. Washington, USA	44.30	288.70	1.24	1.26
Mt. Wellington, Australia	-42.92	147.24	1.89	1.95
Ottawa, Canada	45.40	284.40	1.08	1.10
Pic Du Midi, France	42.93	0.25	5.36	5.29
Predigtsthul, Germany	47.70	12.88	4.30	4.26
Rome, Italy	41.90	12.52	6.30	6.12
Sacramento Peak, USA	32.72	254.25	4.98	5.02
Sanae, Antarctica	-70.30	357.65	1.06	1.00
Sulphur Mt., Canada	51.20	244.39	1.14	1.12
Uppsala, Sweden	59.85	17.58	1.41	1.39
Ushuaia, Argentina	-54.80	291.70	5.68	5.68
Utrecht, The Netherlands	52.06	5.07	2.76	2.70
Yakutsk, Russia	62.02	129.72	1.70	1.63
Zugspitze, Germany	47.42	10.98	4.24	4.27

Table 3.3 Effective vertical cutoff rigidities for CR stations calculated using two geomagnetic field models for the epoch 1955.0 (According to Shea and Smart, 1975a)



Fig. 3.32 Illustration of penumbra delineated at 0.001 GV (*left* in each double column) and 0.01 GV (*right*) for Palestine ($31.75 \circ N$, $95.65 \circ W$) for the real geomagnetic field of the epoch 1965.0 (IGRF model). White indicates allowed and dark indicates forbidden CR trajectories (According to Smart and Shea, 1975b)

and Shea's (1975b) results of penumbra trajectory-traced numerical calculations for two delineated values: 0.001 and 0.01 GV.

Analysis of the results shown in Fig. 3.32 led Smart and Shea (1975b) to the following conclusion: the main cone cutoff (4.72 GV for penumbra delineated at 0.01 GV and 4.756 GV for delineated at 0.001 GV) and the effective cutoff rigidity (4.48 and 4.468 GV) are quite similar, but there are serious differences in the Störmer cutoff rigidity (4.38 GV compared with 3.828 GV).

3.11.2 The Concept of the First Forbidden Band in the CR Penumbra

Smart et al. (2000), in their extended review on the CR geomagnetic effects, accentuated the important role of the pioneering works of Lund et al. (1970, 1971) and Peters (1974) realizing the use of CR geomagnetic cutoff features to measure actual CR phenomena. Lund et al. (1971) noted a feature they called the first forbidden band that was generally stable and could be used as a sharp edge for isotope separation (Byrnak et al., 1981; Soutoul et al., 1981). The concept of this first forbidden band is illustrated in Fig. 3.33. The rigidities illustrated are the relatively simple trajectories that intersect the solid earth as the rigidity scan passes through the upper cutoff rigidity. These relatively simple trajectories, forming the first forbidden band, also form a relatively stable and persistent feature of the CR penumbra. They generated the sharp edge that the HEAO 3 experimenters used for isotope separation (Copenhagen-Saclay, 1981).

According to Smart et al. (2000), the specific feature of the first forbidden band can also be used as a check of the absolute accuracy of the trajectory calculations. The concept is that 100% of the CR flux is transmitted at rigidities above the rigidity of the first forbidden band. The first forbidden band is the fiducially mark that normalizes both the theoretical and observed transmission. The transmission decreases as a function of rigidity as the forbidden bands in the CR penumbra block particle access. The trajectory calculations offer a prediction of the rigidity of the first forbidden band and the relative transmission through the CR penumbra (see for more detail in Section 3.12).

3.11.3 Penumbral Width in Dependence of Vertical Cutoff Rigidity for Different Epochs

The penumbral width Δ is determined as the difference between the main cone cutoff rigidity and Störmer cutoff rigidity. In Smart and Shea (1975b), on the basis of trajectory-traced penumbra function calculations penumbra widths for each location for world grids at epochs 1955.0, 1965.0, and 1975.0 of real magnetic field models were determined. Results are shown in Fig. 3.34 for the epochs 1955.0, 1965.0, and 1975.0.

According to Smart and Shea (1975b), the examination of Fig. 3.34 suggests that, up to about 10 GV, the width Δ of the penumbra is fairly well ordered when using the main cone vertical cutoff rigidity R_{cm} as an ordering parameter; a least-squares fit to the data for each epoch results in the following relationships:

$$\Delta(1955.0) = 0.098 R_{cm}^{1.326}, \quad \Delta(1965.0) = 0.138 R_{cm}^{1.171}, \quad \Delta(1955.0) = 0.140 R_{cm}^{1.175},$$
(3.137)

where Δ is in GV.

3.11.4 Effective Vertical Cutoff Rigidities for Different CR Detectors and Types of CR Variations

The problem of determining the effective vertical cutoff rigidities for different CR detectors and types of CR variations in the dipole approximation of the geomag-







Fig. 3.34 The penumbral width Δ vs. main cone vertical cutoff rigidity for the epochs 1955.0, 1965.0, and 1975.0 (According to Smart and Shea, 1975b)

netic field was considered in detail in Chapter 2 (Section 2.7). We described in Eqs. 2.123–2.129 how the effective vertical cutoff rigidity can be determined for different geomagnetic latitudes, different CR detectors, and different types of CR variations if the penumbra function f(R) is known. Table 2.2 and Fig. 2.11 show how for three geomagnetic latitudes 30° , 40° , and 50° the effective vertical cutoff rigidity changed for different types of observations in dependence of the rigidity spectrum of primary CR variation. Let us note that Eqs. 2.123–2.129 may also be used for the case of the real geomagnetic field. Only for each point of observation it is necessary to use the specific penumbra function f(R) determined from numerical trajectory calculations in the interval $R_{\min} - R_{\max}$ where it takes the values 0 or 1 correspondingly for forbidden and allowed trajectories, and f(R) = 0at $R < R_{\min}$, f(R) = 1 at $R > R_{\max}$. Therefore, for the real geomagnetic field the effective geomagnetic cutoff rigidity R_{cik} for a type *i* detector recorded on the some altitude with pressure h_o , characterized by the polar coupling coefficient $W_{oi}(R, h_o)$, and a type k variation of the primary spectrum $\Delta_k D(R) / D(R)$ will be determined by the equation

$$\int_{R_{\min}}^{R_{\max}} f(R) W_{oi}(R, h_o) \frac{\Delta_k D(R)}{D(R)} dR = \int_{R_{cik}}^{R_{\max}} W_{oi}(R, h_o) \frac{\Delta_k D(R)}{D(R)} dR.$$
 (3.138)

In the relatively small interval $R_{\min} - R_{\max}$, the coupling coefficients can be represented in the form of a power function

$$W_{oi}(R,h_o) \propto R^a, \tag{3.139}$$

where *a* is positive in the low-energy region and negative for large *R*. Similarly, the primary variation can be represented in this interval by

3.11 The CR Penumbral Effects in the Real Geomagnetic Field

$$\frac{\Delta_k D(R)}{D(R)} \propto R^b. \tag{3.140}$$

The integrand on the right-hand side of Eq. 3.138 can then be written as

$$W_{oi}(R,h_o)\frac{\Delta_k D(R)}{D(R)} = A \times R^{\gamma}, \qquad (3.141)$$

where $\gamma = a + b$ and *A* is a constant, irrelevant for further computations. The function f(R) can be represented in the form

$$f(R) = \begin{cases} 1 & \text{for } R_{2m-1} \le R \le R_{2m}, \\ 0 & \text{for } R_{2m} \le R \le R_{2m+1}, \end{cases}$$
(3.142)

where *m* are integers, and $1 \le m \le n$ with $R_1 = R_{\min}$, $R_{2n+1} = R_{\max}$. Substitution of Eq. 3.142 into Eq. 3.138, taking into account Eq. 3.141, gives

$$\sum_{m=1}^{n} \left(R_{2m}^{\gamma+1} - R_{2m-1}^{\gamma+1} \right) = R_{\max}^{\gamma+1} - \left(R_{cik} \left(h_o \right) \right)^{\gamma+1},$$
(3.143)

whence we find for the required effective cutoff rigidity

$$R_{cik}(h_o) = \left[R_{\max}^{\gamma+1} - \sum_{m=1}^{n} \left(R_{2m}^{\gamma+1} - R_{2m-1}^{\gamma+1} \right) \right]^{\frac{1}{\gamma+1}}.$$
 (3.144)

For the actual geomagnetic field, f(R) was computed in Shea et al. (1965b) for four different points (Fig. 3.35).



Fig. 3.35 Penumbra function f_c for four points based on a field model with six spherical harmonics: I, II, III, and IV are based on Finch and Leaton (1957) for the epoch 1955.0 (According to Shea et al., 1965b)



Fig. 3.36 Effective cutoff rigidity in the actual geomagnetic field as a function of γ for points I–IV with coordinates shown in Fig. 3.35 (According to Dorman and Gushchina, 1967)

The corresponding effective cutoff rigidities $R_{cik}(h_o)$ as a function of the exponent $\gamma = a + b$, are given in Fig. 3.36.

With the aid of Fig. 3.36, the expected variations of $R_{cik}(h_o)$ for various CR components and different types of variation can easily be found (see Table A3.12). Even in a quiet period at point I $R_{cik}(h_o)$ varies between 7.901 and 8.037 GV depending on the type of component recorded. The corresponding intervals for the points I–IV are: 4.700–4.757 GV; 4.603–4.651 GV; 3.680–3.795 GV; and 2.0135–2.0240 GV.

As can be seen from Table A3.12, important changes are expected for CR variations of different origin. Namely, for the neutron component at sea level in intervals: 7.938–7.78 GV, 4.718–4.677 GV, 3.716–3.637 GV, and 2.0225–2.0045 GV for the points I, II, III, and IV, correspondingly. For the hard component at sea level in intervals: 7.987–7.825 GV, 4.730–4.689 GV, and 3.747–3.668 GV, for points I, II, and III. It should be pointed out that the effective $R_{cik}(h_o)$ also depends on the representation of the field. According to Dorman and Gushchina (1967), for point II the difference between the two representations (Finch and Leaton, 1957 and Jensen and Cain, 1962) in a quiet period is 0.097 GV for recording on low satellites, 0.093 GV for the neutron component at sea level, and 0.112 GV for the hard component at sea level.

3.12 CR Rigidity Transmittance Functions

3.12.1 The Concept of the Transmittance Function and Two Methods of Calculation

According to Shea and Smart (1971) and Shea et al. (1973), the CR rigidity transmittance function is the evaluation of the fraction of allowed trajectories at a specified rigidity that can be detected by a CR experiment possessing a finite solid angle of acceptance. This function was introduced for the first time in Shea and Smart (1971). In order to obtain the rigidity transmittance function $T(R, \lambda, \varphi, H)$, it is necessary to calculate the fraction of allowed trajectories $F(R, \lambda, \varphi, H, \theta, \phi)$ at a given rigidity R, latitude λ and longitude φ , and altitude H arriving in the direction describing by zenith angle θ and azimuthal angle ϕ . The function $F(R, \lambda, \varphi, H, \theta, \phi)$ must then be weighted by the differential geometric factor $dG(\theta, \varphi)/d\theta d\varphi$ of the CR experiment, as described by the following equation (Lezniak et al., 1975):

$$T(R,\lambda,\varphi,H) = \frac{\int\limits_{\theta} \int\limits_{\phi} F(R,\lambda,\varphi,H,\theta,\phi) \left(dG(\theta,\phi) / d\theta d\phi \right) d\theta d\phi}{\int\limits_{\theta} \int\limits_{\phi} \left(dG(\theta,\phi) / d\theta d\phi \right) d\theta d\phi}.$$
 (3.145)

There are two methods for calculating the CR rigidity transmittance function.

The first method: trajectory-traced calculations. Shea et al. (1973) assumed that the CR trajectory calculations for a specific zenith and azimuth (considered to be the midpoint of a small solid angle) typify the CR rigidities allowed (or forbidden) for a finite solid angle. The calculations of the trajectories were made by the trajectorytracing method (see Section 3.5) used in McCracken et al. (1962), Shea et al. (1965) for the epoch 1965.0 according to the geomagnetic field model IAGA (1969) for CR research on balloons at Dallas, Palestine, and Midland. For the Palestine trajectory calculations were performed every 5° in zenith and 30° in azimuth (total 217 different zenith and azimuth angles). For example, the set of trajectory calculations for the zenith angle 15° and azimuth angle 60° is considered to be representative of all trajectories in the solid angle boundaries by $12.5-17.5^{\circ}$ in zenith and $45-75^{\circ}$ in azimuth. To illustrate this, Fig. 3.37 shows penumbra functions for zenith angles 15° , 30° , and 45° , as the first step in the calculation of the transmittance function. The second step is the determination of effective cutoff rigidities in each direction (as described in Section 3.11), and then integrating over the acceptance solid angle.

The second method: empirical by using the Störmer equation. The abovedescribed trajectory-traced method of CR rigidity transmittance function calculation is very complicated, and needs a lot of computer time; it can be applied to several important points, but for many CR stations, it is better to apply the empirical method by using the Störmer equation proposed by Shea et al. (1973). The idea of this method is to use vertical effective cutoff rigidity R_{cv} determined by trajectory-traced calculations, and then determine the effective geomagnetic latitude



Fig. 3.37 The first step of CR rigidity transmittance function calculation by the trajectorytraced method. Illustration of penumbra calculated at zenith angles of 15° , 30° , and 45° for Palestine (Texas, USA). The azimuthal directions are (from *left* to *right*): 277° , 307° , 247° , 337° , 217° , 7° , 187° , 37° , 157° , 67° , 127° , and 97° . All azimuthal directions are measured clockwise from the north. For comparison, penumbra for the vertical direction is also shown (denoted by the letter V) (According to Smart and Shea, 1975b)

 λ_{ef} according to the expression

$$\lambda_{\rm ef} = \arccos\left(R_{cv}/\left(M_E/r^2\right)\right)^{1/4},\tag{3.146}$$

where M_E is the dipole magnetic moment of the earth, and *r* is the distance from the point of CR measurements to the center of the dipole. In this case, an approximate value of cutoff rigidity in any direction can be calculated very easily by using the Störmer equation determining the main, open cone (see Chapter 2):



Fig. 3.38 The comparison of results obtained by empirical and trajectory calculated methods of determining the CR rigidity transmittance function for Palestine (Texas, USA) for CR detectors possessing 45° and 60° half-angle apertures (*left* and *right* panels, correspondingly) (According to Shea et al., 1973)

$$R_c(r,\theta,\phi,\lambda_{\rm ef}) = \frac{M_E \cos^4 \lambda_{\rm ef}}{r^2 \left(1 + (1 - \sin\theta\sin\phi\cos^3\lambda_{\rm ef})^{1/2}\right)^2},\tag{3.147}$$

where θ is the zenithal angle, and ϕ is the azimuthal angle. After determining $R_c(r, \theta, \phi, \lambda_{ef})$, it is necessary to make integration over θ and ϕ covered all accepted solid angles.

Figure 3.38 shows the comparison of results obtained by the above-described two methods of determining the CR rigidity transmittance function for Palestine (Texas, USA) for CR detectors possessing 45° and 60° half-angle apertures.

3.12.2 The Dependence of Transmittance Function Calculation Accuracy from the Delineated Value

In Bobik et al. (2001) the transmittance functions, using the Tsyganenko (1989) field model, are calculated with rigidity delineated values $\Delta R = 10^{-3}$, 10^{-4} , and 10^{-5} GV, for the high-latitude CR station Oulu (65.05° N, 25.47° E). Results are shown in Fig. 3.39.

From Fig. 3.39 sufficient difference can be seen between calculated transmittance functions for 10^{-3} GV and 10^{-4} GV delineated values, but for 10^{-4} GV and 10^{-5} GV delineated values, the difference between calculated transmittance functions is negligible. From this it follows that, for high-latitude sites, the optimum delineated value is 10^{-4} GV. Fig. 3.39 Results of computations of the transmittance function for Oulu NM, as for 10 UT on January 21, 1986 (low geomagnetic activity) using Tsyganenko's (1989) external field model with rigidity delineated values $\Delta R = 10^{-3}$ - 10^{-5} GV (from *top* to *bottom*) (According to Bobik et al., 2001)



3.12.3 The Dependence of Transmittance Function Calculation Accuracy from the Number of Azimuthal Directions

Figure 3.40 shows results of Smart and Shea's (1975a) calculations using the trajectory-traced method of transmittance functions for Sioux Falls, Cape Giradeau, and Palestine for two cases: when transmittance functions are calculated on the basis of 4 and 12 azimuthal directions. From Fig. 3.40 it can be seen that most exact results gave calculations of transmittance functions on the basis of 8 and 12 azimuthal directions.

For Dallas and Midland, calculations were made for a total of 73 different zenith and azimuth angles. Results are shown in Fig. 3.41 in comparison with those obtained for Palestine.

3.12.4 On the Influence of Ionization Losses on the Transmittance Function

Lezniak et al. (1975) investigated the influence of ionization losses on the transmittance function. The ionization losses of a CR primary particle in the atmosphere were considered in detail in Rossi (M1952) and by Sternheimer (1959):



Fig. 3.40 Transmittance functions calculated by the trajectory-traced method for Sioux Falls, Cape Giradeau, and Palestine on the basis of 4 azimuthal directions (*top* panel) and of 8 and 12 azimuthal directions (*bottom* panel) (From Smart and Shea, 1975a)

$$\frac{\mathrm{d}\left(E_{k}/A\right)}{\mathrm{d}x} = 1.536 \times 10^{-4} \frac{Z^{2}}{A\beta^{2}} \left(9.30 + 2\ln\left(\beta\left(1-\beta^{2}\right)^{-1/2}\right) - \beta^{2}\right) \frac{\mathrm{GeV/nucleon}}{\mathrm{g/cm^{2}}},$$
(3.148)

where E_k/A is the kinetic energy per nucleon of a primary CR particle with charge Ze, β is the particle velocity divided by light velocity, and *x* is the distance along the trajectory in g/cm². For determining *x*, it is necessary to know the distribution of air density $\rho(H)$ depending on altitude *H* that can be described by the equation



Fig. 3.41 Transmittance functions calculated by the trajectory-traced method for Dallas and Midland in comparison with those obtained for Palestine (According to Shea et al., 1973)



$$\rho(H) = \frac{0.3530}{T(H)} \exp\left(-34.17 \int_{0}^{H} \frac{dH'}{T(H')}\right) \quad g/cm^{3}, \quad (3.149)$$

where the atmospheric temperature profile T(H) used in Lezniak et al. (1975) is shown in Fig. 3.42.

In Fig. 3.43 the transmittance function for the balloon experiment at an altitude of 40 km over Cape Giradeau is shown for oxygen primary CR particles in the case where ionization losses have been considered.

A comparison of smoothed transmittance functions for Cape Giradeau calculated without energy loss along particle trajectories (see Fig. 3.39) and taking into account energy loss along particle trajectories (see Fig. 3.43) is shown in Fig. 3.44.



Fig. 3.44 Comparison of CR rigidity transmittance functions for Cape Giradeau for different assumptions (According to Lezniak et al., 1975)

It can be seen from Fig. 3.44 that, for CR primary particles with Z = 6 and more, the account of ionization losses along particle trajectories is sufficient for calculations of CR rigidity transmittance functions.

3.12.5 On the Checking of the Theoretically Calculated CR Rigidity Transmittance Functions by Balloon Experiments

Webber et al. (1975) described the experiment which can be used for checking the theoretically calculated CR rigidity transmittance functions. The experiment was made during balloon flights at Cape Giradeau ($R_c = 2.62 \text{ GV}$) and Sioux Falls ($R_c = 1.71 \text{ GV}$) using CR telescopes (including Cherenkov counters) of highenergy resolution. Near the cutoff, the energy resolution of Cherenkov counters was $\sim 60 \text{ MeV/nucleon}$. As was shown in Webber et al. (1975), one can study details of both the isotopic composition of CR and the rigidity cutoff of the earth's magnetosphere by examining the pulse-height distributions obtained for the various CR charges in a Cherenkov detector onboard a high-altitude balloon at a latitude where the rigidity cutoff is slightly above the threshold energy of the Cherenkov detector or with a scintillation \times total energy measurement when the rigidity cutoff is below the Cherenkov threshold. If we select a CR element which we know consists essentially of a single isotope (e.g., oxygen), then we can study the shape of the rigidity transmittance function and compare it with one that is theoretically determined. On the other hand, if we know exactly the rigidity transmittance function, we may study the cutoff effects of other CR nuclei thus deriving information on their isotopic composition.

Figure 3.45 presents a pulse-height distribution obtained for CR oxygen nuclei using a lucite Cherenkov detector onboard a high-altitude balloon from Cape Giradeau (the solid curve denotes the expected distribution in the absence of geomagnetic cutoff).

In order to determine the details of the rigidity cutoff, Webber et al. (1975) had taken various possible rigidity transmittance functions and used them to calculate pulse-height distributions, which were then compared with experimental data as shown in Fig 3.45. In Fig. 3.46 a comparison between the observed and calculated pulse-height distributions is presented for two assumed forms of the rigidity trans-



Fig. 3.45 Observed pulse-height distribution obtained for CR oxygen nuclei with a lucite Cherenkov detector onboard a high-altitude balloon from Cape Giradeau. The expected distribution in the absence of geomagnetic cutoff is shown by the solid curve (According to Webber et al., 1975)



Fig. 3.46 Comparison of observed and calculated pulse-height distributions. The observed pulse-height distribution is the same as that presented in Fig. 3.45, and is reproduced twice at the lower pulse height channels so that it may be readily compared with the two separate calculations of the pulse-height distribution obtained under different assumptions of the shape of the rigidity cutoff (According to Webber et al., 1975)



Fig. 3.47 Rigidity transmittance functions for Cape Giradeau for a CR telescope with a halfacceptance angle of 30° for different assumptions (According to Webber et al., 1975)

mittance function: one which is predicted theoretically using the trajectory-tracing technique (see Sections 3.12.1–3.12.3) and one which represents a sharp cutoff.

In Fig. 3.47 a plot is presented of the rigidity transmittance functions used to generate the calculations shown in Fig. 3.46.

As was shown by Webber et al. (1975), the observation data are consistent (see Fig. 3.46) with a sharp cutoff but are also consistent with a somewhat more gradual transmittance function, as shown in Fig. 3.47. This gradual transmittance function was obtained from the observation data by using a numerical deconvolution technique to invert the integral equation and so obtain the product of the rigidity transmittance function and the kinetic energy spectrum. Then, by dividing the obtained result on the kinetic energy spectrum, the rigidity transmittance function was determined (as shown in Fig. 3.47).

3.12.6 On Checking the Theoretically Calculated CR Rigidity Transmittance Functions by Satellite Experiments

According to Smart et al. (2000), the difference between the predicted transmission and the observed transmission seen in the satellite experiment is an indication of the accuracy of the trajectory calculations. The HEAO-3 experimenters (Copenhagen-Saclay, 1981) found that, at 5 GV, the experimentally observed first forbidden band in their ¹⁶O data set was about 5% lower than predicted by the trajectory calculations using the IGRF internal field. These results are shown in Fig. 3.48.

However, at about 2 GV larger differences were found between the experimental observations of the first forbidden band and the trajectory calculations utilizing the IGRF field model. There was a larger shift between the predicted and observed rigidity of the first forbidden band, as shown in Fig. 3.49, and the observed penumbra was more transparent than predicted by the trajectory calculations.



Fig. 3.48 Calculated and experimentally observed CR cutoff at 5 GV by the HEAO-3 experiments at an altitude of 400 km. The heavy line indicates the predicted transmission through the CR penumbra obtained by trajectory calculations in the internal geomagnetic field. The light line indicates the observed average transmission derived from several thousand primary CR oxygen nuclei (According to Copenhagen-Saclay, 1981)



Fig. 3.49 Calculated and experimentally observed CR cutoff at 2 GV by the HEAO-3 experiments at 400 km altitude. The solid line indicates the predicted transmission through the CR penumbra obtained by trajectory calculations in the internal geomagnetic field. The dashed line indicates the observed average transmission derived from several thousand oxygen nuclei (According to Copenhagen-Saclay, 1981)

The results shown in Fig. 3.49 indicate the inadequacy of trajectory calculations using only the internal geomagnetic field to describe the trajectory of charged particles in the magnetosphere. These results also strongly suggest (Smart et al., 2000) that at rigidities below a few GV, the use of magnetospheric models is essential for reliable CR trajectory calculations.

3.12.7 Transmittance Function Approach to Disentangle Primary from Secondary CR Fluxes in the Penumbra Region

According to Bobik et al. (2006), the AMS-01 observations (in June 1998, onboard the space shuttle orbiter Discovery) have shown the presence of primary and secondary CRs (most of them protons) at a low earth orbit (at about 400 km of altitude). In this paper the transmittance function has been determined for each of the ten geomagnetic regions (see Table 3.4 and Fig. 3.50), M = 1, 2, 3, ... 10, for which the AMS-01 data are available and is indicated by T_M . These regions are defined by means of the corrected geomagnetic coordinates (CGM, see in http://nssdc.gsfc.nasa.gov/space/cgm/cgm.html). CGM coordinates (latitude and longitude) of a point in space are computed by tracing the DGRF/IGRF magnetic field line through the specified point to the dipole geomagnetic equator, then returning to the same altitude along the dipole field line and assigning the obtained dipole latitude and longitude as the CGM coordinates to the starting point.

Region M	CGM latitude θ_M (rad)	Kinetic energy (GeV)
1	$ \theta_{\rm M} \le 0.2$	6.16
2	$0.2 \le \theta_{\rm M} \le 0.3$	6.16
3	$0.3 \le \theta_{\rm M} \le 0.4$	4.88
4	$0.4 \le \theta_{\rm M} \le 0.5$	3.00
5	$0.5 \le \theta_{\rm M} \le 0.6$	3.00
6	$0.6 \le \theta_{\rm M} \le 0.7$	1.78
7	$0.7 \le \theta_{\rm M} \le 0.8$	1.35
8	$0.8 \le \theta_{\rm M} \le 0.9$	0.74
9	$0.9 \le \theta_{\rm M} \le 1.0$	0.27
10	$ \theta_{\rm M} \geq 1.0$	0.07

Table 3.4 Geomagnetic regions covered by AMS-01 measurements and kinetic energies corresponding to each geomagnetic zone (From Bobik et al., 2006)



Fig. 3.50 The ten geomagnetic regions (M) covered by AMS-01, defined in Table 3.4, are shown on the background of the Earth surface. A typical trajectory of AMS-01 detector onboard the space shuttle, at an altitude of about 400 km, is also plotted. The space shuttle trajectory shifts with time and covers the earth's surface almost uniformly inside a geographic latitude $|\theta_{glat}| \leq 51.6^{\circ}$ (From Bobik et al., 2006)

Bobik et al. (2006) note that the T_M requires the determination of the allowed trajectories of the particles entering the AMS-01 spectrometer, following a backtracking procedure. The 3,600 locations of the particles to be backtracked are distributed uniformly over a complete sphere surrounding the earth at an altitude of 400 km and 78.9% of them are within the geographic latitudes of the orbits of the space shuttle, i.e., $|\theta_{\text{glat}}| \leq 51.6^{\circ}$, excluding the South Atlantic anomaly region. The 270 particle directions are isotropically distributed within the outward hemisphere and inside the 32° acceptance cone (around the local geocentric zenith) of the AMS-01 spectrometer. In addition, a large number of particle directions covering up to the full outward hemisphere have been backtracked to investigate the T_M dependence on the acceptance cone. The T_M has been computed for the same 31 rigidity intervals of the AMS-01 data (see in Aguilar et al., 2002, Table 4.5), i.e., the lowest rigidity value is about 0.37 GV and the largest is about 200 GV. To take into account the energy dependence of the proton flux, each energy interval has been subdivided into ten equally spaced subintervals. The subintervals have been weighted according to the function of their relative fluxes. Within the acceptance cone of the AMS-01

spectrometer, about 2.3×10^8 particle trajectories have been reconstructed back to the magnetopause or to the atmosphere.

For the ten geomagnetic regions, the T_M has been averaged over all uniformly distributed locations:

$$T_M(R_b) = \sum_{i_M} \frac{T_M(R_b, i_M)}{\sum i_M},$$
(3.150)

where R_b is the particle rigidity in the *b*th rigidity interval of width ΔR_b , $T_M(R_b, i_M)$ is the transmittance function for the position i_M inside the geomagnetic region M, and Σi_M is the total number of locations for the same region. For the location i_M , $T_M(R_b, i_M)$ is given by:

$$T_M(R_b, i_M) = \sum_{s=1}^{10} \frac{w_{b,s} N_{all}^{i_M}(R_{b,s})}{N_{all}^{i_M}(R_{b,s}) + N_{forb}^{i_M}(R_{b,s})},$$
(3.151)

where $R_{b,s}$ and $w_{b,s}$ are the mean rigidity and weight of the *s*th subinterval of the width $\Delta R_b/10$ for the *b*th rigidity bin, $N_{all}^{i_M}$ and $N_{forb}^{i_M}$ are the numbers of allowed and forbidden trajectories, correspondingly.

In Fig. 3.51, the T_M for the ten different AMS-01 geomagnetic regions (given in Table 3.4) and during the STS-91 AMS-01 flight are shown as a function of the proton kinetic energy in GeV. As expected, toward the polar regions lower-energy particles can reach the AMS-01 orbit through the magnetosphere. In Fig. 3.52 the transmittance functions for the first and tenth geomagnetic regions are shown as functions of the proton kinetic energy for detector acceptance cones of 32° (i.e., the AMS-01 acceptance cone) and 45° (i.e., the expected AMS-02 acceptance cone)



Fig. 3.51 Transmittance function $T_{\rm M}$ evaluated for AMS-01 regions during the STS-91 mission flight time (June 1998) as a function of the proton kinetic energy in GeV. The lines are to guide the eye (From Bobik et al., 2006)



Fig. 3.52 Transmittance function for: **a** T_1 and **b** T_{10} in dependence of the proton kinetic energy for detector acceptance cones of 32° and 45° around the local geocentric zenith. The lines are to guide the eye (From Bobik et al., 2006)

around the local geocentric zenith. The smaller the acceptance cone, the steeper the T_M becomes. However, for geomagnetic regions beyond the fifth, the transmittance functions become similar.

The major contributions to the quoted errors for the transmittance functions in Figs. 3.51 and 3.52 are about 1.4% for the uncertainty of the spectral index of the primary proton spectrum used in the subintervals, about 1% for AMS-01 altitude variation during the observation time, and about 1.5% (in total) for the algorithm accuracy, treatment of the magnetic field model, and procedure of the speed optimization. Furthermore, although the T_M has been computed for June 8, 1998, at 10.00 UT, the T_M does not vary by more than 0.1% during the AMS-01 observation duration at different daytimes for fixed geomagnetic condition (constant

 $D_{st} = -22 nT$, evaluated as average for full AMS-01 mission flight time). Thus in the ten geomagnetic regions, the AMS-01 observed flux has been set (and indicated with $\Phi_{M,N}^{obs}(R_b)$) at 1 AU for rigidities larger than those of the penumbra region for each geomagnetic region:

$$\Phi_{M,N}^{obs}(R_b, T_M(R_b) = 1) = \Phi_{1AU}(R_b, T_M(R_b) = 1).$$
(3.152)

For rigidities where $T_M(R_b) = 0$, i.e., below the penumbra rigidities in each geomagnetic region, the observed fluxes have not been corrected, i.e.,

$$\Phi_{M,N}^{obs}(R_b, T_M(R_b) = 0) = \Phi_M^{obs}(R_b, T_M(R_b) = 0).$$
(3.153)

Inside the penumbra regions for which $0 < T_M(R_b) < 1$, the observed fluxes in each geomagnetic region M have been corrected to take into account(1) the effective detection of high-energy particles, i.e., the average difference among the observed flux and the corresponding flux at 1 AU in each rigidity bin above about 20.5 GeV of kinetic energy (these are energies large enough to neglect the geomagnetic-dependence of the regions), and (2) the effective detection for each penumbra rigidity bin, i.e., the average difference among the observed flux and the corresponding flux at 1 AU in the same rigidity bin of the successive regions (with larger geomagnetic latitudes) where $T_M = 1$. As an example, in Fig. 3.53, the fluxes per units of solid angle $\Phi_{M,N}^{obs}(R_b)$ are shown for the geomagnetic regions 1, 4, 7, and 10 as functions of the proton kinetic energies. The errors accounting for the correction procedure have been added quadratically to the published errors for the observed fluxes from Alcaraz et al. (2000a). For the AMS-01 observations, the predicted primary CR fluxes per unit of solid angle $\Phi_M(R_b)$ are obtained by convolving the



Fig. 3.53 Normalized fluxes per units of solid angle are shown for the geomagnetic regions M = 1, 4, 7, and 10 as functions of the proton kinetic energies. The lines are to guide the eye (From Bobik et al., 2006)

transmittance function of each geomagnetic region M with the estimated AMS-01 flux $\Phi_{1AU}(R_b)$ (given in Alcaraz et al., 2000b) at 1 AU, i.e., outside the magnetosphere, as functions of the proton rigidity R_b . Thus, it will be

$$\Phi_M(R_b) = \Phi_{1AU}(R_b) T_M(R_b). \qquad (3.154)$$

The secondary CR fluxes per unit of solid angle $\Phi_M^s(R_b)$ can be obtained as

$$\Phi_{M}^{s}(R_{b}) = \Phi_{M,N}^{obs}(R_{b}) - \Phi_{M}(R_{b}).$$
(3.155)

As examples, in Figs. 3.54–3.57 the fluxes per units of solid angle $\Phi_{1AU}(R_b)$, $\Phi_M(R_b)$, and $\Phi_M^s(R_b)$ are shown as functions of the proton kinetic energy for the first, fourth, seventh, and tenth geomagnetic region. The quoted errors for the fluxes $\Phi_M(R_b)$ and $\Phi_M^s(R_b)$ have been derived by the error propagations from those of the transmittance functions $T_M(R_b)$ and fluxes $\Phi_{1AU}(R_b)$ and $\Phi_{M,N}^{obs}(R_b)$.

Bobik et al. (2006) came to the following conclusions:

- 1. The AMS-01 observations (in June 1998, onboard the space shuttle orbiter Discovery) have shown the presence of primary and secondary CRs at a low earth orbit, i.e., at an altitude of about 400 km.
- 2. Most of these secondary CRs are trapped or fast reentrant albedo protons created in interactions with the atmosphere by fast incoming primary CRs.
- 3. Some secondary particles seem to be sufficiently energetic to populate the penumbra region above the local geomagnetic cutoff rigidity.
- 4. A backtracking procedure of simulated protons entering the AMS-01 spectrometer provides the fraction of allowed (and hence forbidden) trajectories of primary CRs. Consequently, it allows determining of the transmittance function describ-



Fig. 3.54 Fluxes per units of solid angle as a function of the proton kinetic energy for M = 1 geomagnetic region: $\Phi_{1AU}(R_b)$ – open circles, $\Phi_{M=1}(R_b)$ – solid circles), and $\Phi_{M=1}^s(R_b)$ – squares (From Bobik et al., 2006)



Fig. 3.55 The same as in Fig. 3.54, but for M = 4 geomagnetic region



Fig. 3.56 The same as in Fig. 3.54, but for M = 7 geomagnetic region

ing the transport properties of primary CRs to the space surrounding the earth (at an altitude of about 400 km) from the upper limit of the geomagnetic field, i.e., the magnetopause located at 1 AU.

- 5. The transmittance function finally allows determining of fluxes of the primary CRs in the ten geomagnetic regions for AMS-01 observations.
- 6. The observed spectra of the AMS-01 geomagnetic regions are found to be larger that those predicted for the primary CRs in the penumbra region by the transmittance function procedure, i.e., some secondary CRs (mainly reentrant albedo protons) are also found to populate the spectrum above the local geomagnetic cutoff rigidity.



Fig. 3.57 The same as in Fig. 3.54, but for M = 10 geomagnetic region

- 8. The fraction of the secondary to overall particle flux in the penumbra region increases gradually to more than about 28% in the ninth geomagnetic region (i.e., for latitudes between 0.9 and 1.0 rad); owing to earth shadowing, this excess is only present in the downward proton flux.
- 9. The models IGRF (1992) and Tsyganenko96 (Tsyganenko and Stern, 1996) of geomagnetic fields used to determine the transmittance function can be extrapolated for the coming years, as a consequence the transmittance function can be derived for the same period of time. Since the modulated CR spectrum at 1 AU can also be estimated for coming years, it becomes possible to predict particles fluxes at any observation location of future experiments inside the magnetosphere.

3.13 Obliquely Incident Particles and Apparent Cutoff Rigidities

Obliquely incident particles have been considered in the computations of asymptotic-approach directions (Rao et al., 1963; Cramp et al., 1995). Stoker (1995) suggested that oblique particles might also be responsible for anomalies in neutron monitor latitude surveys. Clem et al. (1997) proposed an operational definition of a parameter that they named the "apparent" cutoff rigidity. The apparent cutoff rigidity is defined as that rigidity which, if uniform over the whole sky, would yield the same neutron monitor counting rate as the real, angle-dependent, cutoff rigidities distribution. Clem et al. (1997) calculated propagation of primary CR particles through the earth's atmosphere with the three-dimensional Monte Carlo transport program FLUKA (FLUctuating KAscades) maintained at INFN in Milan, Italy (Fassò et al., 1993). An initially isotropic distribution of primary particles is filtered through a map of the effective geomagnetic cutoff rigidities calculated

for each geographical location and the surviving particles transported through the atmosphere. The simulated ground-level particle intensities, folded with the NM-64 detector response, are then used to calculate a geographically dependent NM-64 counting rate. One important result of these calculations is that the response with an increasing angle of incidence, falls less rapidly than predicted by an exponential relationship on $\sec(\theta)$ as would be expected from a simple attenuation model. Scattering in multiple inelastic interactions removes most memory of the primary incidence direction from a daughter particle at sea level. Such multiple interactions thus reduce the attenuation of obliquely incident particles. Figures 3.58 and 3.59 illustrate these calculations for two different locations.

In each case the cutoff map was obtained by computing the effective cutoff rigidities in 41 separate directions, and then using a standard contour plotting algorithm to generate the map (these calculations take about three days of CPU time on a DEC Alpha workstation for one position). In Fig. 3.58, the apparent cutoff rigidity found is close to the vertical cutoff rigidity, whereas in Fig. 3.59 there is a substantial difference between the apparent and vertical cutoff rigidities. The primary conclusion of Clem et al. (1997) is that the apparent cutoff rigidities provide a far superior ordering of the CR latitude survey data sets.

While the apparent cutoff rigidity is clearly superior to the vertical cutoff rigidity in ordering the data, it also takes about 40 times as long to calculate. Bieber et al.



Fig. 3.58 Effective cutoff rigidities map for location 48.19° S, 77.02° W. Vertical cutoff rigidity is 7.37 GV, and apparent cutoff rigidity is 7.38 GV. Solid dots show the locations where cutoffs are calculated for the ring approximation (According to Bieber et al., 1997)



Fig. 3.59 The same as in Fig. 3.58, but for location 43.92°S, 76.64°W. Vertical cutoff rigidity is 8.23 GV, and apparent cutoff rigidity is 8.65 GV (According to Bieber et al., 1997)

(1997) therefore tried to find what approximations may be valid. A first approximation is of course a simple trend line such as that shown in Fig. 3.60. Such a line is probably sufficient to allow latitude surveys analyzed with apparent cutoff rigidities to be compared with surveys using vertical cutoff rigidities. Most truly systematic effects on derived particle spectral indices should be reduced greatly using this device. It is interesting to note that the "world grid" cutoff rigidities all lie close to the trend line, in distinction from those emerging from the Clem et al. (1997) analysis. That analysis was, however, specifically prompted by a large anomaly in the counting rates, ultimately traced to the structure observed between 6 and 10 GV in Fig. 3.60.

In an attempt to find a faster way to calculate cutoffs in such a region – or perhaps as a way to identify such regions – Bieber et al. (1997) have considered an approach reminiscent of that employed by Rao et al. (1963). Bieber et al. (1997) consider effective cutoffs computed for nine directions (large black dots in Figs. 3.58 and 3.59). Their approximation to the apparent cutoff is the average of the vertical cutoff rigidity and the average cutoff rigidities over the ring at 30° off vertical. They used a weight of 1/2 for the vertical cutoff rigidity, and for the eight cutoffs at 30° a weight of 1/16 each. Figure 3.61 shows the result of this approximation, i.e., the difference between the ring method approximation of cutoff rigidity and the apparent cutoff rigidity as function of vertical effective cutoff rigidity.



Fig. 3.60 Difference between apparent and vertical cutoff rigidities as a function of effective vertical cutoff rigidity (According to Bieber et al., 1997)



Fig. 3.61 Difference between apparent and vertical cutoff rigidities as a function of effective vertical cutoff rigidity (From Bieber et al., 1997)

A comparison of Figs. 3.60 and 3.61 shows most of the large scale-trend is removed in this approach and a significant amount of the fine structure as well. Specifically, the RMS error from the trend line in Fig. 3.60 is 0.08 GV, whereas the scatter is reduced to 0.05 GV in Fig. 3.61 (relative to the trend line shown there). Most encouraging is the "anomalous" structure in Fig. 3.60 which is reproduced fairly well under the ring approximation in Fig. 3.61. Scatter in this region is no worse than it is for the "world grid" points.

3.14 Simulation of the Geomagnetic Cutoff Rigidity Angle Distribution with the GEANT-3 Computing Program Using the Data of the International Geomagnetic Reference Field

3.14.1 Importance of the Exact Knowledge of the CR Cutoff Rigidity Angle Distribution for the Problems of Atmospheric Neutrino and Other Secondary Particles Generated in the Earth's Atmosphere

As pointed out by Wentz et al. (2001a), a precise knowledge of the CR geomagnetic cutoff rigidity R_c angle distribution is a substantial ingredient in any calculation of low-energy particle fluxes in the earth's atmosphere. Especially the calculation of atmospheric neutrino fluxes for the investigation of the Atmospheric Neutrino Anomaly, requests precise directional-dependent tables of R_c functions. The Super-Kamiokande experiment in Kamioka, Japan, delivered the most precise results on the Atmospheric Neutrino Anomaly (Fukuda et al., 1998), existing substantial differences between neutrinos produced above the detector, and the neutrinos produced in the antipode region in the South Atlantic. This observation is commonly interpreted as clear evidence for neutrino oscillations. Nevertheless, there are also geographical differences between Japan and the South Atlantic which have to be taken into consideration. Due to the South Atlantic Magnetic Field Anomaly, the geomagnetic cutoff in Japan is about 50% higher than at the opposite point of the earth. In addition, the experimental observation of a directional East–West dependency of the neutrino fluxes (Futagami et al., 1999) has to be accounted mainly to the asymmetry in the primary particle flux caused by R_c , while the deflection of charged secondary particles, like pions and muons in the atmosphere, plays a minor but not negligible role (the problem of geomagnetic field influence on CR secondary components generated and propagated in the atmosphere will be consider in more detail in Section 3.15).

In Wentz et al. (2001a) the International Geomagnetic Reference Field is used in a GEANT-3 simulation to calculate R_c for CRs entering the earth's magnetic field. The calculations are made using the backtracking method, where antiprotons start

from the top of the atmosphere and are tracked to outer space. The R_c functions are estimated for protons in rigidity steps of 0.2 GV for 131 directions in 1,655 locations covering, in a nearly equidistant grid, the surface of the earth. For special locations, where neutrino or low-energy muon data have been measured, the R_c functions are calculated in a fine grid of 21,601 directions.

The estimated R_c can be verified by the experimental results for primary protons and helium nuclei measured in different geomagnetic latitudes during the Shuttle mission of the AMS prototype. These precise tables of R_c can be used in the frame of the CORSIKA code to calculate atmospheric muon and neutrino fluxes.

3.14.2 Using the Backtracking Method for the Precise Calculation of the Geomagnetic Cutoff Rigidities

In Wentz et al. (2001a), the simulation of R_c is done in a complete microscopic calculation of possible proton trajectories in a realistic magnetic field of the earth. Only the trajectories connecting outer space with the earth's surface represent particles above the geomagnetic cutoff rigidities R_c . Thus, the simulation of R_c can be reduced to the problem of calculating these trajectories. Due to the possibility of inverting the problem, the calculation of R_c can be made using the backtracking method, where antiprotons start from the earth's surface and are tracked until they reach outer space, where the magnetic field vanishes, or they are bent back to the earth. Assuming an isotopic primary flux in outer space, which is only disturbed by the presence of the earth and its magnetic field, the directional particle intensity can be calculated by taking out all forbidden trajectories, expressed in a table of R_c , depending on the geographical position, the local arrival direction, and the rigidity of the particle. This is a direct consequence of applying Liouville's theorem, as has been already proved by Lemaitre and Vallarta (1933) and Störmer (1930).

As the starting altitude of the backtracking method, the top of the atmosphere at an elevation of 112.3 km was selected by Wentz et al. (2001a). This particular choice of the starting altitude allows the direct use of the results within the COR-SIKA simulation program (Heck et al., 1998). The magnetic field inside the earth's atmosphere and the deflection of charged particle in it is handled in CORSIKA (CORSIKA is a code widely used for the simulation of Extensive Air Showers). The extension by the tables of R_c now allows the simulation of low-energy primary particles, too. The antiprotons are tracked with the GEANT-3 detector simulation tool (CERN, 1993). Due to the unusual dimensions for a GEANT-3 simulation, the tracking precision has to be investigated. The tracking can be tested by reversing the trajectory, meaning that the momentum and charge of the antiproton are inverted, after the particle leaves the magnetosphere and the reversed particle is traced on its way back to the starting point. The error found by this method is about 10 m. Compared with a typical track length of 50,000 km, this means a relative tracking error of $\approx 2 \times 10^{-7}$. The earth's magnetic field is described by the International Geomagnetic Reference Field (IAGA, 1992) for the year 2000. This allows a precise simulation of the penumbra region, too. While a pure dipole field always leads to a sharp cutoff, the precise irregular field with its inhomogeneities partly shows a diffuse region between the closed trajectory of the highest and open trajectories of the lowest rigidity.

3.14.3 Calculations and Results for the Planetary and Angle Distributions of CR Geomagnetic Cutoff Rigidity

In Wentz et al. (2001a), geomagnetic cutoff functions have been simulated for 1,655 locations, distributed nearly equidistantly over the earth's surface. The functions are simulated in 320 rigidity steps in a range between 0.4 and 64.4 GV for 131 arrival directions. The rigidity range covers all energies from the particle production threshold up to the maximum cutoff of a particle impinging horizontally at the geomagnetic equator from the East. The simulation of the complete cutoff functions in fixed rigidity steps allows the study of the smoothness of the cutoff, the sometimes chaotic behavior of the cutoff in some regions, and the existence of gaps for the primary protons well below the geomagnetic cutoff. The chosen resolution of 0.2 GV is sufficient for calculating of atmospheric particle fluxes. The obtained world map of the vertical geomagnetic cutoff rigidities R_c is shown in Fig. A3.1.

For some selected places, where experimental results exist for low-energy muons or atmospheric neutrinos, precise tables of R_c with an angular resolution of 250 μ sr have been calculated. As an example, the directional-dependence of R_c for Fort Sumner, in New Mexico, is presented in Fig. A3.2 (Fort Sumner has been used by many balloon-borne detectors as a launching place).

Figure A3.3 displays the sharpness of the cutoff, defined by the momentum difference between the first open and the last closed trajectory. In the case of Fort Sumner, the cutoff is relatively sharp; especially for directions with a higher cutoff the penumbra region is rather narrow or not found at all.

Fig. A3.4 shows the directional-dependence of the geomagnetic cutoff rigidity for Kamioka.

It is remarkable that for Kamioka the strong deviation from a regular shape as observed in the calculation for Fort Sumner (Fig. A3.2) is caused by some local irregularities of the magnetic field over Japan. This feature should be reflected in the azimuthal-dependence of the particle intensity in Kamioka.

The broad penumbra region in Kamioka is interesting. As seen in Fig. A3.5, the penumbra region has a width of more than 4 GV in some cases (this is about four times broader than in the calculation for Fort Sumner, while the maximum cutoff in both locations is practically comparable).

Figure A3.5 also shows the existence of cutoff gaps, meaning that windows for primary protons, some GV below the actual cutoff, are observed. Especially in the region around a zenith angle of 25° and an azimuth angle of 160° this effect is very pronounced and explains the chaotic behavior observed in the geomagnetic cutoff

map. This feature is the result of higher-order corrections of the magnetic field in this direction and can be accounted for only in a detailed calculation, like the one presented in Wentz et al. (2001a). Usual calculations with a pure dipole field used in many simulations of atmospheric particle fluxes fail completely in reproducing this effect. Due to the steep spectra of primary CRs, the contribution of primary protons from such a gap may have a significant contribution to the neutrino flux from this direction.

3.14.4 Comparison with AMS Measurements of the Geomagnetic Cutoff on Shuttle

According to Alcaraz et al. (2000a, b, c), the geomagnetic cutoff was measured with high precision by the space Shuttle mission of the Alpha Magnetic Spectrometer (AMS) prototype. Due to the inclination of 51.7° of the Shuttle orbit, the Shuttle passes geomagnetic latitudes from 0 to more than 1 rad. The experimental spectra of downward moving protons and helium nuclei can be compared rather directly with the results of the above-described simulation. Only a small correction in the order of 10% for the difference in altitude between the top of the atmosphere, as assumed in CORSIKA and the shuttle orbit is applied. In detail, the position of the Shuttle and the detector acceptance are taken into account in Wentz et al. (2001a). Locations situated in the region of the South Atlantic Magnetic Field Anomaly are excluded, as they are in the published values of AMS. The primary isotropic spectra are simulated following the measured exponential energy spectra but being extrapolated downward to particle energy E = 0. The solar modulation is assumed to follow the parameterization of Gleeson and Axford (1968). Particles above the geomagnetic cutoff and inside the detector acceptance are sorted out and compared with the measured spectra. The spectra of primary protons for different regions of the geomagnetic latitude together with the simulation results are shown in Fig. A3.6, while Fig. A3.7 displays the corresponding results for primary helium nuclei.

The lower flux of primary helium allows only the subdivision into three intervals of the geomagnetic latitude. The excellent agreement of the actual cutoff calculation with the experimental results shows the high precision of the calculation, only the proton spectrum for geomagnetic latitudes $0.9 < \theta_{mag} < 1.0$ shows a slight difference, which has to be attributed to the smallness of the cutoff value which is more or less equal to the momentum steps of the cutoff functions. This disagreement has no influence on the simulation of atmospheric neutrino and muon fluxes, because the involved energies are already near the particle-production threshold and the produced secondary particles hardly reach the earth's surface with a valuable energy.

Wentz et al. (2001a) came to the conclusion that the measured spectra of primary protons and helium nuclei show perfect agreement with the calculated values of the geomagnetic cutoff. For selected locations on the earth, where low-energy atmospheric neutrino or muon fluxes have been measured, detailed calculations in 21,601 directions for the geomagnetic cutoff have been made. The resulting cutoff tables have been used for the simulation of atmospheric muon fluxes and the simulation of the neutrino fluxes for the Super-Kamiokande site with CORSIKA (Wentz et al., 2001b).

3.15 Geomagnetic Field Influence on Secondary CR Generated and Propagated in the Atmosphere

3.15.1 On the Possible Geomagnetic Effects in Secondary CRs

Many of the particles which are produced by the primary CR and which move through the earth's atmosphere are charged, so that their trajectories are affected by the geomagnetic field. As CRs propagate through the earth's atmosphere, the energy of the primary particle is reduced by nuclear collisions; in addition, the energy of the charged particles decreases because of ionization energy losses. As the kinetic energy of the charged particle decreases, the curvature of its trajectory increases. The effect of the geomagnetic field on CRs in the atmosphere is thus to deflect charged particles away from their original trajectories. As the trajectory of a charged particle changes, so does its path length (both the geometric path length and the path length in terms of grams per square centimeter) down to a fixed depth in the atmosphere. In addition, there are changes in the coordinates of the point of the interaction with the nucleus. The effectiveness of the geomagnetic field's influence on CR propagation in the atmosphere was demonstrated in Pakhomov (1982) on the basis of the integral multiplicities calculated without considering the specific detector. Involved in Dorman and Pakhomov (1983) are not only the charged particles but also the genetically related neutrons. In Dorman and Pakhomov (1983), calculations were carried out on the propagation of CRs in the atmosphere with allowance for the effect of the geomagnetic field. The energy spectra of protons, neutrons, π^{\pm} mesons, and muons are found. The integral neutron multiplicities are determined for the NM-64 neutron supermonitors at various atmospheric depths with and without allowance for the geomagnetic field.

3.15.2 The Main Conditions for Calculations and Principal Sources

Dorman and Pakhomov (1983) report calculations of the differential energy spectra of neutrons N_n , protons N_p , charged pions $N_{\pi^{\pm}}$, and muons N_{μ} from a monoenergetic point source of unit intensity (1 proton/(cm².sec)) at the top of the atmosphere. Calculations were carried out for pion-nucleon cascades in the atmosphere from primary protons with energies $E_o = 3$ and 10 GeV incident vertically on the atmosphere at the point with the coordinates corresponding to the geographic pole. A cascade-evaporation model of nuclear reactions was used incorporating the decrease in the density of nuclear matter due to the ejection of intra-nuclear nucleons by cascade particles, according to Barashenkov et al. (1971), and Barashenkov and Toneev (M1972). The Monte Carlo program library, developed previously by Luzov et al. (1976) for calculations on the propagation of particles in matter, was supplemented with a part to describe the motion of charged particles in the geomagnetic field. The effect of the geomagnetic field on the propagation of charged particles in the atmosphere was taken into account with the help of the equations of motion of particles in a steady state magnetic field with allowance for ionization energy loss:

$$\mathrm{d}p_i/\mathrm{d}t = -\alpha p_i + (e/c) \left[\mathbf{V} \times \mathbf{H}\right]_i, \qquad (3.156)$$

where p_i are the momentum components of the particle, V is its velocity, *e* is its charge, *c* is the speed of light, *H* is the geomagnetic field, and α is a function of the energy of the particle and the density of the air. Using the Bethe–Bloch formula, we find that

$$\alpha = 0.05c\rho \left(1+T\right)^2 \left(T^2 + 2T\right)^{-1/2} \left(\Phi/12\right) \left(M_p/M\right).$$
(3.157)

Here ρ is the density of the air, M_p is the mass of the proton, M is the mass of the particle, T is the kinetic energy in units of the rest mass of the particle, and

$$\Phi \approx 11.6 + \ln\left(T^2 + 2T\right) - \left(T^2 + 2T\right)\left(1 + T\right)^{-2}.$$
(3.158)

The strength of the geomagnetic field was calculated by the ICGRF program, which was developed in Tsyganenko (1979). The first six spherical harmonics of the series were taken into account. The primary protons were assumed incident vertically on an infinite plane slab of air 1033 g/cm^2 thick, consisting of 21% oxygen and 79% nitrogen. The altitude profiles of the pressure and temperature were calculated from the standard atmosphere model (Khrgian, M1958).

3.15.3 Expected Ratios of Secondary CR Neutrons to Muons with and without Allowance for the Geomagnetic Field

Working from the energy spectra calculated with and without allowance for the geomagnetic field, we determined the contributions of the various components to the overall multiplicity of particles which were produced and which reached a fixed level in the atmosphere. Table 3.5 shows the results found in the ratio of the number of neutrons $m_n^{atm}(E_o, E, h)$ to the number of charged particles $m_{ch}^{atm}(E_o, E, h)$ for various levels h (in g/cm²) or corresponding altitudes H (in km) in the atmosphere and for various secondary particle energies E, generated from primary protons with energy E_o incident to the boundary of the atmosphere in the vertical direction.

Energy of secondary particles	Altitude (km)	Primary proton energy 3 GeV		Primary proton energy 10 GeV	
		With geomagnetic field	Without geomagnetic field	With geomagnetic field	Without geomagnetic field
	15	1.9	2.2	1.4	1.9
$E > 10 \mathrm{MeV}$	10	3.4	3.8	2.2	2.5
	5	7.7	5.0	3.0	3.3
	0	383	18.4	1.8	1.5
	15	1.0	1.3	0.8	1.1
<i>E</i> > 100 MeV	10	1.8	2.0	1.2	1.4
	5	4.0	2.7	1.5	1.7
	0	198	5.2	0.73	0.67
	15	0.63	0.81	0.58	0.79
$E > 400 \mathrm{MeV}$	10	1.1	1.2	0.75	0.90
	5	2.1	1.9	0.71	0.80
	0			0.19	0.15

Table 3.5 The ratio of the number of neutrons to the number of charged particles in secondary CRs depending on altitude H and particles energy E, generated by primary protons with energies 3 and 10 GeV (According to Dorman and Pakhomov, 1983)

Table 3.5 shows that the ratio of the number of neutrons to the number of charged particles falls off with increasing energy of the primary particles, particularly rapidly at sea level. These calculations show that the fraction of muons in the total particle multiplicity depends strongly on the energy of the primary particle. At low energies $(E_o = 3 \text{ GeV})$, there are essentially no muons at sea level, while at mountain altitudes and in the stratosphere they amount to no more than 5%. At primary proton energies $E_o = 10 \text{ GeV}$, the fraction of muons increases with the threshold energy and depth in the atmosphere reaching 80% at sea level at E > 400 MeV.

The contribution of charged pions is insignificant, less than 1%. The fraction of protons in the total multiplicity decreases with increasing depth and increases with the threshold energy, amounting to no more than 5% at sea level and reaching 55% in the stratosphere at E > 400 MeV. Correspondingly, the number of neutrons falls off with increasing threshold energy and varies in a complicated way with atmospheric depth. At primary proton energies $E_o = 3$ GeV, the contribution of neutrons increases with depth, amounting to 99.7% at sea level. At $E_o = 10$ GeV, the fraction of neutrons increases with increasing atmospheric depth to H = 5 km and then falls off sharply.

It can be also seen from Table 3.5, that the geomagnetic field causes certain changes in the ratio of the number of neutrons to the number of charged particles. However, the nature of the change in this ratio with depth in the atmosphere and with threshold energy is basically the same as in the results calculated without the

geomagnetic field. Only in the case of primary particles with $E_o = 3 \text{ GeV}$ for E > 10 MeV and E > 100 MeV does the ratio increase dramatically at H = 0 and 5 km.

3.15.4 Expected Differential Energy Spectra N(E) of Secondary Neutrons and Muons at Sea Level and at H = 5 kmfrom Primary CR Protons with Energy 3 and 10 GeV According to Calculations with and Without Geomagnetic Field Influence on Their Propagation in the Atmosphere

Figure 3.62 shows differential energy spectra N(E) of neutrons and muons at sea level and at H = 5 km according to calculations with and without the geomagnetic field. We see from Fig. 3.62 that, for primary protons with $E_o = 3 \text{ GeV}$,



Fig. 3.62 Differential energy spectra N(E) of secondary neutrons and muons at altitudes H = 0 (sea level) and at H = 5 km generated from 1 proton/(cm².sec) with energies $E_o = 3$ and 10 GeV incident vertically on the atmosphere and calculated with and without the geomagnetic field (solid and dashed curves, respectively) (According to Dorman and Pakhomov, 1983)
the differential energy spectra of neutrons at H = 0 and of muons at mountain altitudes (H = 5 km) calculated without the geomagnetic field, are significantly higher than the corresponding values found with the geomagnetic field in the region $E \leq 100-150 \text{ MeV}$. At $E_o = 10 \text{ GeV}$, the particle spectra are less different. Incorporating the geomagnetic field leads to an increase of 20–30% for the neutrons over a broad energy range.

The muon spectra calculated with the geomagnetic field for $E_o = 10 \text{ GeV}$ exceed the equivalent values calculated without the field up to $E \leq 300-400 \text{ MeV}$. The energy spectra for the various particle species thus change substantially when the geomagnetic field is taken into account.

3.15.5 Differential Energy Spectra of Neutrons, Protons, Charged Pions and Muons at Sea Level and Altitudes 5, 10, 15 km Generated from Primary Protons with Energies 3 and 10 GeV According to Calculations Taking into Account the Geomagnetic Field Influence on Secondary CR Particles Propagation

Figure 3.63 shows differential energy spectra of neutrons, protons, π^{\pm} mesons, and muons according to calculations incorporating the geomagnetic field.

Figure 3.63 shows that the neutron energy spectra are monotonically decreasing functions of the energy, while the spectra of protons, π^{\pm} mesons, and muons have a maximum. At $E_o = 3 \text{ GeV}$, the neutron fluxes are considerably higher than the fluxes of other components at all atmospheric depths considered and over the entire energy range. For primary protons with $E_o = 10 \text{ GeV}$, the neutron fluxes exceed the fluxes of the other components at energies $E \leq 300-400 \text{ MeV}$. At higher energies E, at mountain altitudes and altitudes in the stratosphere, the neutron fluxes become comparable to the proton and muon fluxes, while the muon fluxes become predominant at sea level.

We should point out that the proton energy spectra rise sharply near the energy of the primary particles. This "trace of the primary particles" is noticeable in the proton energy spectra at stratospheric altitudes (H = 15 and 10 km) and at mountain altitudes (H = 5 km). It can be seen from Fig. 3.63 that the primary protons with $E_o = 3$ GeV produce at H = 15 km proton fluxes at $E \approx 2.5$ GeV – an energy approximately equal to the energy of the primary particles (when the ionization loss is taken into account) – which are 2.5 times the fluxes of the primary protons with $E_o = 10$ GeV. The energy spectrum of the primary CR falls off steeply with the energy. At $\gamma = 2.7$, there are 25 times as many primary protons with $E_o = 3$ GeV as with $E_o = 10$ GeV. The primary protons with $E_o = 3$ GeV thus make a contribution to the proton flux in the stratosphere (H = 15 km) near the energy $E \approx 2.5$ GeV which is 65 times as great as that of primary protons with $E_o = 10$ GeV.

3.15.6 On the Detector's Integral Multiplicity Taking Account of Geomagnetic Field Influence on Secondary CR Particle Propagation

Since the trace of the primary particles intensifies with decreasing depth in the atmosphere and is extremely noticeable at depths of $100-250 \text{ g/cm}^2$, there is the possibility of detecting variations in the primary cosmic radiation on aircraft. A limitation of this method is that the detectors must carefully identify the particle species (protons, α -particles, and others). As mentioned above, the geomagnetic field is important for neutrons in the atmosphere with $E \leq 100-150 \text{ MeV}$. According to Hughes et al. (1964), neutron monitors of the NM-IGY type mostly detect neutrons with $E \geq 50 \text{ MeV}$. The calculations of Pakhomov and Sdobnov (1977) show that the NM-IQSY neutron supermonitor is sensitive to lower energy of neutrons: each tenth neutron with E = 10-20 MeV is thus detected. We would like to determine the changes in the integrated neutron multiplicities m_n caused by taking the geomagnetic field into account in the case of the NM-IQSY neutron supermonitor. By the detector's integral multiplicity $m_i(E_o, h)$ we mean the number of particles of species *i* which are detected at observation level *h* and which are produced from a single primary particle of energy E_o which has entered the atmosphere in a vertical



Fig. 3.63 Differential energy spectra of neutrons (n), protons (p), charged pions (π^{\pm}) , and muons (μ) according to calculations incorporating the geomagnetic field for altitudes H = 15, 10, 5, and 0 km and primary protons with energies $E_o = 3$ and 10 GeV incident vertically on the atmosphere (According to Dorman and Pakhomov, 1983)

Table 3.6 Detector's integral multiplicities for the neutron supermonitor NM-IQSY for observations at sea level and at an altitude of 5 km from primary protons with energies 3 and 10 GeV, according to calculations with and without the geomagnetic field (According to Dorman and Pakhomov, 1983)

Primary proton energy	$H = 5 \mathrm{km}$		$H = 0 \mathrm{km}$ (sea level)	
	Without geomagnetic field	With geomagnetic field	Without geomagnetic field	With geomagnetic field
$E_o = 3 \text{GeV}$ $E_o = 10 \text{GeV}$	0.17 0.48	0.21 0.58	0.011 0.029	0.063 0.039

direction:

$$m_i(E_o,h) = \int_0^{E_o} m_i^{atm}(E_o,E,h)G_i(E) dE, \qquad (3.159)$$

where $G_i(E)$ is an instrumental function which is a measure of the efficiency at which particles of species *i* with energy *E* are detected, and $m_i^{\text{atm}}(E_o, E, h)$ is the number of particles of species *i* which are produced in the atmosphere and which reach the level *h*. Table 3.6 shows the results of calculation of the detector's integral multiplicities for the neutron supermonitor NM-IQSY. From Table 3.6 it can be seen that the detector's integral neutron multiplicities calculated with and without allowance for the geomagnetic field are quite different. We might note that the differences reach a maximum at sea level, 75% for primary proton energy $E_o = 3 \text{ GeV}$ and 26% for $E_o = 10 \text{ GeV}$.

3.15.7 On Checking Geomagnetic Field Effects on Secondary CRs During their Propagation in the Atmosphere using Data from High-Latitude CR Stations

The analysis in Sections 3.15.1–3.15.6 shows that the geomagnetic field has a strong effect on the secondary components of the CR in the atmosphere up to an energy of 100–150 MeV for nucleons and 300–400 MeV for muons. Theoretical calculations of the integral multiplicities, detector's integral multiplicities, and coupling functions must therefore incorporate the effect of the geomagnetic field on the propagation of CRs in the atmosphere. Since the effect of the geomagnetic field on CRs in the atmosphere is the greatest for low-energy primary particles (with energies in the order of a few GeV), experimental confirmation of this effect should be sought in data from high-latitude CR stations.

3.16 On the Influence of IMF on the CR Entry into the Earth's Magnetosphere

3.16.1 The Matter of Problem

Richard et al. (2002) have investigated the entry of energetic ions of solar origin into the earth's magnetosphere as a function of the orientation of the interplanetary magnetic field (IMF). They modeled this entry by following high-energy particles (protons and ³He ions) ranging from 0.1 to 50 MeV in electric and magnetic fields from a global MHD model of the magnetosphere and its interaction with the solar wind. For the most part, these particles entered the magnetosphere on or near open field lines, except for some above 10 MeV that could enter directly by crossing field lines due to their large gyro-radii. The MHD simulation was driven by a series of idealized solar wind and IMF conditions. It was found that the flux of particles in the magnetosphere and transport into the inner magnetosphere varied widely according to the IMF orientation for a constant upstream particle source, with the most efficient entry occurring under southward IMF conditions. The flux inside the magnetosphere could approach that in the solar wind, implying that SEPs can contribute significantly to the magnetospheric energetic particle population during typical SEP events depending on the state of the magnetosphere.

The goal of Richard et al.'s (2002) study was to understand the entry of SEPs into the magnetosphere and under what conditions they contributed significantly to the magnetospheric particle population. While the most energetic solar particles will not be strongly deflected by magnetospheric magnetic fields, the entry of a large fraction of the incoming energetic particles will be influenced by the magnetospheric configuration, which is in turn controlled by the IMF. Richard et al. (2002) approached the problem of SEP entry into the magnetosphere by calculating many particle trajectories in MHD field models of the magnetosphere under different IMF conditions. They focused on the transport of SEPs into the inner magnetosphere that provides the source population for the ring current.

3.16.2 The MHD Model of the Magnetosphere for Different IMF Conditions

Richard et al. (2002) computed the trajectories of high-energy particles subject to the Lorentz force equation including relativistic modifications. Because these highenergy particles have large Larmor radii, a guiding center approximation would be inadequate. The electric and magnetic field model in which they determined the trajectories of these particles, was obtained from a global MHD simulation of the magnetosphere and its interaction with the solar wind (Raeder et al., 1995). MHD simulations provide the best available three-dimensional global models of the entire magnetosphere and its interaction with the solar wind, as shown by their ability



Fig. 3.64 MHD input parameters: the IMF conditions used to drive the MHD simulation as a function of time (According to Richard et al., 2002)

to model spacecraft observations (Frank et al., 1995). MHD simulations have been used with some success as field models for thermal particle motion in the magnetosphere (Richard et al., 1994, 1997; Ashour-Abdalla et al., 1997). SEPs in the solar wind are very tenuous compared to the bulk (low energy) solar wind and they would not disturb the field model significantly, with the possible exception of the ring current region. For this study, Richard et al. (2002) primarily launched protons, but they also launched some ³He ions because of their importance as indicators of impulsive solar particle events.

To simplify the interpretation of the results, Richard et al. (2002) used idealized solar wind and IMF conditions (Fig. 3.64) to drive the simulation. According to Fig. 3.64, the B_v and B_z components of the IMF were assumed to vary during the simulation while the IMF B_x component was held at -5 nT. For the first hour and a half of the simulation, B_z was southward with a magnitude of 5 nT to initialize the simulation. From between 1.5 and 3.5 h, B_z was southward with a magnitude of 8 nT. A 2-hour interval of steady IMF allowed the model magnetosphere to respond to this driving condition. Previous MHD simulations have shown that a timescale of 1-2h is needed for the magnetosphere to reach a new configuration following a change in the IMF (Ogino et al., 1994; Walker et al., 1999). During this southward IMF interval solar wind, i.e., not connected to the earth, field lines reconnected with closed field lines on the dayside, while in the magnetotail, open field lines reconnected to make solar wind and closed field lines. Richard et al. (2002) varied the IMF linearly in time between 3 h 30 min and 4 h until it was dawnward and then held it steady with $B_y = 8 \,\mathrm{nT}$ from hour 4 to 6. This led to a magnetospheric configuration with open field lines on the dawn-side flank of the magnetosphere. From hour 6 to 6 h 30 min, the IMF changed to northward IMF and remained steadily northward with a magnitude of 8 nT until hour 8.

For northward IMF conditions, reconnection occurred tailward of the cusp. In general, the magnetospheric configurations were similar to those seen in previous MHD simulations for idealized IMF conditions (e.g., Walker and Ogino, 1989). Particles were launched for a longer interval of time in the northward and dawnward IMF configurations than in the southward based on the assumption that, during the first 3 h of the simulation, the magnetosphere had already responded to the southward IMF condition. Other solar wind parameters did not change with time. The solar wind density remained fixed at 10 cm^{-3} , and its velocity was 450 km/s in the *x* direction and the thermal pressure was 20×10^{-12} Pa. One feature of the simulation that was not included in many idealized simulations was a constant magnetic dipole tilt angle of 33° . The resulting hemispheric asymmetry was increased further because of the presence of an IMF B_x . Besides tilting the dayside magnetosphere, the tilt and the B_x depressed the plasma sheet below z = 0 and warped it dawnward in the center versus the flanks.

According to Richard et al. (2002), the entry of the high-energy particles into the magnetosphere is strongly affected by the presence of open magnetic field lines. The variation of the fraction of open magnetic flux on the inner boundary as a function of time (see Fig. 3.65) reflects the morphological evolution of the model magnetosphere.

From Fig. 3.65 it can be seen that for southward IMF, the fraction of open flux is more than half. After the transition to dawnward IMF, the fraction of open flux dec-



Fig. 3.65 Fraction of open magnetic flux as a function of time. This was calculated by integrating the amount of open and closed flux through the inner boundary sphere at 4.5 r_e and dividing the amount of open flux by the total. The shaded bands indicate the times when the IMF was changing. The IMF direction is also indicated: SW stands for southward, DW for dawnward, and NW for northward (According to Richard et al., 2002)

reased for about 0.45 min and then stabilized and increased slightly. After the transition to northward IMF, the fraction of open magnetic flux decreased to an even lower level. Overall, the simulations were arranged driving conditions to be appropriate for generating a series of representative magnetospheric states. Launching a constant upstream flux in this system allowed us to attribute changes in the particle population in the magnetosphere to the effect of the magnetospheric configuration.

3.16.3 Calculations of CR Particle Trajectories

The particle trajectories in Richard et al. (2002) were calculated in the time-varying fields from the MHD simulation and they experienced different field configurations as time advanced. This was done by interpolating linearly in time between snapshots of the simulation fields taken every 4 min. Protons were launched every minute between simulation hours 3 and 8, while ³He ions were launched only for southward IMF, i.e., between hours 3 and 3.5. A total of 9.4 million protons were launched, as well as about 1 million ³He ions. High-energy particles from the sun reach the earth, streaming along interplanetary magnetic field lines (Flückiger, 1990). Richard et al. (2002) therefore launched the test particles (protons and ³He ions) upstream of the magnetosphere in the solar wind. Figure 3.66 shows where they were launched for southward IMF.



Fig. 3.66 Particle launches for southward IMF. In this figure all items are at or projected into the y = 0 plane. The thin lines are magnetic field lines begun at y = 0 at the sunward boundary. Particles were launched on planes whose locations are indicated by the heavy lines. The other curves are fits to the magnetopause and bow shock and the x = 0 and y = 0 planes. The small circle represents the location of the earth. Note the presence of dipole tilt and B_x (From Richard et al., 2002)

Particles were launched near the sunward boundary on a plane in the solar wind at $x = 15 r_{\rm E}$ extending between $-35 r_{\rm E}$ and $35 r_{\rm E}$ in y and in z. SEPs from a single distant source arriving at the earth's surface along interplanetary field lines arrive either parallel to or antiparallel to the interplanetary field lines. Because the IMF B_x was negative, particles that entered the system from the sunward direction were moving along magnetic field lines. Particles that are moving along field lines should enter the simulation system at other locations where field lines are directed into the system as well. All locations at the side, bottom, or top boundary where field lines were directed into the simulation region, were presumed to be particle sources. For example, for the southward IMF case particles were launched along the top boundary as well as the front boundary as well as at $x = 15 r_{\rm E}$ (Fig. 3.66). Because particle distributions were modified by interaction with the bow shock, Richard et al. (2002) launched particles only in the region $x > -11 r_{\rm E}$ near where the bow shock intersects the system boundary; with this limit, however, some particles were launched in the magnetosheath because the bow shock position varied in time and this limit was an approximation.

3.16.4 Particle Distribution in Velocity Space

According to Richard et al. (2002), the particles were distributed in velocity space as a kappa distribution (Christon et al., 1988) with a κ coefficient of 0.5. The formula for a kappa distribution function is

$$F(E) \approx \left(1 + E/\kappa E_{\rm T}\right)^{-\kappa - 1},\tag{3.160}$$

where *E* is the particle energy and E_T is the thermal energy. For $E \gg E_T$, this becomes a power law with a coefficient of $-(\kappa + 1)$. The thermal energy used was set to a value near 40 keV. The energy range of particles launched was between 0.1 and 50 MeV. Particles below 100 keV were not included in the distribution because the study concerned particles above typical magnetospheric energies; and particles above 50 MeV have Larmor radii comparable to the system size were also not included. The launched distribution was isotropic except for the fact that only particles with velocities into the simulation system were included.

Particles reaching the outer boundaries of a box with edges at $x = 18 r_{\rm E}$, $x = -100 r_{\rm E}$, $y = \pm 40 r_{\rm E}$ and $z = \pm 40 r_{\rm E}$ were removed as were those reaching a 4.5 $r_{\rm E}$ radius sphere centered on the earth which is outside the simulation inner boundary at 3.5 $r_{\rm E}$. The particles reaching this boundary were considered to have precipitated. Particle "hits" were collected at planar and spherical virtual detectors (Ashour-Abdalla et al., 1993). Particles that cross these surfaces have the time, positions, and velocities of their crossing recorded. Particle fluxes and other quantities can be calculated from these values. Note that in the results shown in this paper flux at a virtual detector is the omnidirectional flux; i.e., the contributions of all the particles crossing a given virtual detector surface from any direction in a given region

(chosen to be $1r_E^2$ squares) are added together. The flux at virtual detectors scale with the source in the upstream solar wind. Because particles are launched from $x > -11r_E$ only, particles that could arrive on open field lines that reached the simulation boundary tailward of the bow shock, are neglected. Because the $E \times B$ drift in the solar wind was small compared to the velocities of the energetic particles, they usually did not convect to these parts of the polar cap either. This left part of the polar cap empty in considered results. If the system size in y and z had been large enough to include all open field lines on the sunward side, the polar cap would probably have been more completely filled.

3.16.5 How the Magnetosphere Reaches a Quasi-Steady Configuration Consistent with Each IMF Direction

Since Richard et al. (2002) carried out their calculations using a time-dependent IMF, it is necessary to ask how the assumed time-dependence (Fig. 3.64) influences the results. In this idealized problem, Richard et al. (2002) wanted to show how particles enter the magnetosphere for a given IMF orientation. Therefore, it is necessary that the magnetosphere has enough time to reach a quasi-steady configuration consistent with each IMF direction. However, trapped particles can remain in the model magnetosphere for a long time compared to the time between IMF orientations. Even after the IMF reaches a quasi-steady state for a given IMF, some of the particles may have entered the magnetosphere when the IMF had a different orientation. To help us understand the effects of the time-dependence on these results, Richard et al. (2002) carried out a series of calculations of particle trajectories for which the electric and magnetic fields were held constant. For these runs, they used the electric and magnetic fields from single time steps in the MHD simulations. By comparing the time-dependent results with the results from these snapshots, we can estimate the significance of the time-dependence.

3.16.6 Calculation Results for IMF in a Southward Orientation

At the beginning of the particle calculations, at hour 3, the IMF was in a southward orientation, and remained so until hour 3.5 at which time the IMF began its transition to a dawnward (positive B_y) orientation. Recall that there was a constant B_x throughout the entire simulation. At hour 4 the IMF transition was complete. During the southward IMF condition, reconnection takes place on the dayside and in the magnetotail. Omni-directional particle fluxes (protons/area-time) during the interval from hour 3 to 3.5 are shown in Fig. 3.67. The upper panel shows the fluxes at the z = 0 plane and the lower panel shows the y = 0 plane for the interval between hours 3 and 3.5. Fits to the bow shock and magnetopause in the MHD simulation are shown as black curves. The dotted curves are the inner boundary of the particle calculation at 4.5 r_E .



Fig. 3.67 Omni-directional particle fluxes accumulated at virtual detectors. The upper panel shows the fluxes at the z = 0 plane and the lower panel shows the y = 0 plane for the interval between hours 3 and 3.5. Fits to the bow shock and magnetopause in the MHD simulation are shown as black curves. The dotted curves are the inner boundary of the particle calculation at 4.5 r_E . Nonzero fluxes appear just inside the inner boundary because the fluxes are collected in $1 r_E^2$ domains. In the magnetosphere, the regions of highest flux had the order of 1,000 hits (one particle can hit a virtual detector more than once) per domain at a virtual detector while the smallest fluxes could reflect a single hit (From Richard et al., 2002)

Nonzero fluxes appear just inside the inner boundary because the fluxes are collected in $1r_{\rm E}^2$ domains. One important feature of the results at this and subsequent times was how effective the magnetospheric magnetic fields were in shielding the magnetosphere from the high-energy solar protons. The bow shock and the magnetopause reflected most incoming protons. Note that the omni-directional flux of

particles upstream of the bow shock was often greater than the incident flux of particles launched. This was because of the contribution of particles reflected from the bow shock; recalling that particles passing through virtual detector planes in either direction were added to compute the omni-directional flux, whereas in the incident flux all ions cross an upstream virtual detector in the same direction. There is a region of low omni-directional flux, relative to adjacent magnetosheath and magnetospheric regions, just outside the magnetopause on the dawn side. This region contains open field lines that extend dawnward away from the earth and then southward to the bottom boundary where particles were not launched during this interval. The ³He ions we launched under southward IMF qualitatively followed the distribution of the protons but their flux within the magnetosphere was generally lower relative to their upstream abundance.

A significant number of ions did penetrate the magnetosphere. Richard et al. (2002) have observed two entry mechanisms for the ions we launched. As we will see later, ions with energies greater than about 10 MeV have Larmor radii large enough that they can directly penetrate the magnetosphere on the dayside, while lower-energy ions moved along open field lines into the magnetosphere. The coefficient of adiabaticity k, the square root of the ratio of the particle Larmor radius to the field line curvature (Bűchner and Zelenyi, 1989) for these energetic particles often fell to values of around 1 or less and they can experience non-adiabatic behavior. This k is not to be confused with the κ coefficient in the distribution function (Eq. 3.160). In the Richard et al. (2002) simulation the directly penetrating particles were energetic enough to experience non-adiabatic behavior over large regions of the magnetosheath and magnetosphere. The locations of open field lines were of primary importance in determining particle entry for the majority of the particles, which were at energies below 1 MeV. Where the magnetic field was weak or had a small radius of curvature, entry was enhanced.

Richard et al. (2002) note the effect of dipole tilt and B_x in Fig. 3.67. Because of these factors, the plasma sheet was warped such that it was lower (in z) near midnight than on the dusk or dawn flanks, and parts of it fell below z = 0. In the magnetotail between hours 3 and 3.5 the protons were mainly confined to the plasma sheet while the lobes were nearly empty. Protons in this plasma sheet were confined within a band of around $5r_{\rm E}$ high in z, but were spread out all along the plasma sheet in y, reflecting the thinness of the plasma sheet for southward IMF. During this time interval (hours 3-4) the protons entered mainly on the front side of the magnetosphere, often through the northern cusp region, visible in Fig. 3.67 near $z = 6r_{\rm E}$, $x = 3r_{\rm E}$. The weak field and open field lines at the northern cusp allowed particles to access the inner magnetosphere. Once inside the magnetosphere, they sometimes became quasi-trapped and began drifting around the earth. While a few protons remained trapped over a relatively long term (hours), most of them reached the inner boundary or entered the plasma sheet and were subsequently lost tailward or at the flanks. The particles that became trapped long enough to completely circle the earth, were adiabatic for the most part and could be energized by the changing local magnetic field responding to the IMF. The cusp, plasma sheet, and the region of quasi-trapped particles are clearly visible in Fig. 3.67, bearing in mind the effect of dipole tilt and consequent plasma sheet warping. The high omni-directional flux of protons visible in the noon–midnight meridian just above z = 0 inside the magnetopause are quasi-trapped particles circulating around the earth. Ions in the equatorial region would probably have approached the earth more closely, and remain trapped longer, but were lost at the inner boundary at $4.5 r_E$. It must be kept in mind that for most of these particles, the trapping is temporary and they leave close field lines again later, frequently returning upstream. While the ions often bounced wildly through the magnetotail, the overall motion was primarily dawn to dusk in the direction of the gradient drift in the tail and trapped particles circled the earth in the expected clockwise sense. It can be seen that omni-directional ion fluxes (Fig. 3.67) reach levels comparable to their fluxes in the solar wind for the quasi-trapping region and the cusp.

To help evaluate the role of time-dependence, Richard et al. (2002) also ran particles in a snapshot of the fields from the MHD simulation taken at 3 h. The flux pattern for this case is shown in Fig. 3.68.

When comparing Fig. 3.68 to Fig. 3.67, it can be seen that the two patterns are remarkably similar. There seems to be a decrease in penetration into the magnetosphere in the time-independent case versus the time-dependent case. This may mean that penetration is enhanced in the time-dependent case, but the effect is evidently secondary in the case of a slowly varying magnetosphere.

3.16.7 Calculation Results for IMF in a Dawnward Orientation

Between hours 4 and 6, the IMF was dawnward. For this configuration, open field lines extended through the dawn flank. This defined the primary entry region for the protons. On the other hand, there is a region with relatively few or no particles just inside the dusk-side magnetopause in the equatorial plane beginning at about $7r_{\rm E}$ from the noon–midnight meridian and extending to the dusk-side boundary (Fig. 3.69 and Fig. 3.70).

Once they entered the plasma sheet, the protons spread out toward the dusk side. Omni-directional fluxes in the quasi-trapping region, the plasma sheet, and the cusp decreased considerably during the interval between simulation hours 4 and 5 (Fig. 3.69). The examination of single-particle trajectories indicated that particles tended to approach the near-earth region from the magnetotail or on the dayside due to direct penetration that was always present. As seen by comparing Figs. 3.67 and 3.69, there was a lower flux of trapped and quasi-trapped particles (between about $9r_E$ and the inner boundary) during the dawnward IMF interval. For this configuration, protons can most easily access the magnetotail from the dawn-side flank, but these protons most commonly exit down the tail and do not reach the inner magnetosphere. The location of maximum flux in the plasma sheet (comparing Figs. 3.67 and 3.69) is now further from the earth, as well as less intense. Because the field lines in the magnetotail are no longer highly stretched protons, they bounce further from the equatorial plane.



Fig. 3.68 The same as in Fig. 3.67 but at 3 h (From Richard et al., 2002)

The interval between 5 and 6 h had a flux distribution qualitatively similar to that of the previous hour (Figs. 3.69 and 3.70). The main difference is an overall decrease in flux and a concentration of high flux to a localized region on the dawn side that did not seem to correspond to any strong localized entry in the MHD simulation. Examining single-particle trajectories indicates that transport in the magnetotail remained primarily from dawn to dusk. For the dawnward case, the time-independent simulation (not shown) gave results similar to the time-dependent case. As was seen in the southward IMF case, however, magnetospheric fluxes in the time-independent case. For both



Fig. 3.69 Particle fluxes between 4 and 5 h. The format is the same as for Fig. 3.67. This interval had a steady dawnward IMF (From Richard et al., 2002)

southward and dawnward IMF particles often partially orbit the earth while mirror bouncing and then exit the magnetosphere, usually tailward or back into the magnetosheath. Others precipitate at the inner boundary after being trapped for a while. If the inner boundary had been closer to the earth, these particles would presumably have remained trapped for a longer period.

3.16.8 Calculation Results for IMF in a Northward Orientation

From 6 to 6.5 h the IMF changed from dawnward to northward, and then remained steady until 8 h. The asymmetry due to dipole tilt and IMF B_x caused more intense



Fig. 3.70 Particle fluxes between 5 and 6 h. The format is the same as for Fig. 3.67. This interval had a steady dawnward IMF (From Richard et al., 2002)

magnetic reconnection to take place in the southern hemisphere, tailward of the cusp, and therefore most open field lines extended southward. The examination of single-particle trajectories indicated that the great majority of the ions in the northern hemisphere entered from a southward direction. Particle entry on the dawn side decreased and fluxes in the southern cusp increased as the field changed (Fig. 3.71). The plasma sheet flux decreased although the maximum moved close to the earth. The lobes on the dawn side contained a low level of energetic particle flux. This flux extends to the noon–midnight meridian plane below the plasma sheet.



Fig. 3.71 Particle fluxes between 6 and 7 h. The format is the same as for Fig. 3.67. The first half hour of this interval was during the transition from dawnward to northward IMF and the second half hour was for steady northward IMF (From Richard et al., 2002)

The flux from 7 to 8 h decreased overall. The most dramatic feature is the high flux in the southern cusp (Fig. 3.72). The magnetopause can be seen to be a strong barrier to particle entry at this time. Particles enter through the southern cusp and high fluxes also occur on the dawn-side LLBL region, though in this case, particles drift across the field and access open field lines, replaced by convection on newly opened field lines (Richard et al., 1994) as the main entry processes.



Fig. 3.72 Particle fluxes between 7 and 8 h. The format is the same as for Fig. 3.67. This interval had a steady northward IMF (From Richard et al., 2002)

3.16.9 Comparison of the Time-Dependent and Time-Independent Cases

When Richard et al. (2002) ran a time-independent case using a snapshot of the northward IMF magnetosphere, at 7 h 45 min, an interesting result was obtained. While the results in the outer magnetosphere were comparable between the time-dependent and time-independent cases, there is much less flux in the inner magnetosphere in the vicinity of the equatorial plane in the time-independent case (Fig. 3.73).



Fig. 3.73 Omni-directional particle fluxes accumulated at virtual detectors for a time-independent case. This calculation used a snapshot from the MHD simulation at 7 h 45 min. The format is the same as for Fig. 3.72 (From Richard et al., 2002)

To understand this difference, Richard et al. (2002) examined the particles that occupied the inner magnetosphere in the time-dependent case. They found that these were trapped or quasi-trapped particles that had entered the inner magnetosphere during earlier times when the IMF orientation was dawnward or southward. We conclude that there were no trapped or quasi-trapped particles observed during the quasi-steady northward IMF simulation that were launched while the IMF was northward.

3.16.10 On the Energy Change of Particles Entering Inside the Magnetosphere

Although the ions were usually non-adiabatic and could gain or lose energy due to magnetospheric electric fields, the high energies of the launched particles relative to the electric potential across the magnetosphere caused energization within the magnetosphere to be of minor importance overall. The exceptions were particle gradient-drifting around the earth for a prolonged interval. These particles experienced adiabatic heating as the magnetic field changed. Waves in the inner magnetosphere that might heat ions further did not play a role in this calculation, even though there are expected to be MHD wave modes present in the simulation, because the sampling of the MHD simulation results every 4 min filtered out almost all waves. To understand the basic physics of particle entry, it is instructive to examine the trajectories of single particles in the model system. The particle trajectories to be discussed now are protons that precipitated onto the inner boundary. Particles of this type were chosen because transport into the nearearth region is important for the results. For southward IMF, protons could access the inner magnetosphere near the northern cusp. One such proton (Fig. 3.74) was launched at simulation time 3 h 32 min and had an initial energy of 107 keV and a 25° pitch angle. This particle began on a solar wind field line on the dawn side and moved toward the magnetosphere. At the magnetopause it experienced a brief interval with $\kappa < 1$ as it crossed from the solar wind to closed field lines. After traveling tailward on the dawn side near the equatorial plane, it was eventually scattered into a nearly perpendicular pitch angle. As it migrated toward the earth and became trapped, which occurred near midnight, κ fell below 1.5. It became trapped and remained so for a prolonged period, finally precipitating after simulation hour 10. This particle experienced adiabatic heating while trapped and its final energy was 190 keV. While this particle was on open field lines only very briefly, it was the strongly curved field lines resulting from dayside reconnection that led to a decrease of κ allowing the particle to enter.

A 611 keV proton launched at 6 h 14 min simulation time, during the transition to northward IMF, is shown in Fig. 3.75. As can be seen from its path in the solar wind, the particle's motion is mainly field aligned there with a pitch angle of 27° . This particle began on solar wind field lines on the dawn side and reached the magnetopause where it became trapped in the magnetopause current layer with a mainly perpendicular pitch angle. It experienced $\kappa < 2$ only during one interval, which is on curved field lines in the magnetosheath. While in the magnetopause current layer, it reached open field lines that it followed inward, and its pitch angle changed to greater than 160°. Later it gained more parallel velocity and precipitated.

Figure 3.76 plots the trajectory of a proton of 390 keV launched at 6 h 26 min simulation time with an initial pitch angle of 63° . As one would expect from the IMF direction at this time, it approached the magnetosphere from the southern, dawnward



Fig. 3.74 Proton trajectory is shaded gray according to field line type and points along a particle trajectory projected onto the z = 0 (*top* panel), y = 0 (*middle* panel), and x = 0 (*bottom* panel) planes are shown. Points where the particle was on closed field lines are dark gray and ones on solar wind field lines are medium gray. Because the total number of points had to be decimated to make this plot, the small number of points on the open field lines are not shown. Filled circles along the trajectory in the top and bottom panels indicate the locations of local minima of κ where $\kappa < 2$. In the middle panel, these points are behind the dense points where the particle is trapped and therefore are not shown. To limit the cluttering of the figure a filled circle was only plotted if it was at least 1.6 r_E away from the others (From Richard et al., 2002)



Fig. 3.75 Proton trajectory is shaded gray according to field line type and points along a particle trajectory projected onto the z = 0 (*top* panel), y = 0 (*middle* panel), and x = 0 (*bottom* panel) planes are shown. Points where the particle was on open field lines are light gray and ones on solar wind field lines are medium gray. Filled circles indicate points that were local minima of κ where $\kappa < 2$ and were more than 1.6 r_E apart (From Richard et al., 2002)



Fig. 3.76 Proton trajectory is shaded gray according to field line type and points along a particle trajectory projected onto the z = 0 (*top* panel), y = 0 (*middle* panel), and x = 0 (*bottom* panel) planes are shown. Points where the particle was on open field lines are light gray and ones on solar wind field lines are medium gray. Filled circles indicate points that were local minima of κ where $\kappa < 2$ that were more than 1.6 $r_{\rm E}$ apart (From Richard et al., 2002)

direction. It crossed into the magnetosphere on the flanks of the magnetotail. Its large Larmor radius in the solar wind is apparent, and this allows it to cross directly from the solar wind to open field lines and finally to closed field lines. It moves on the closed field lines to the inner boundary.

Finally, a definitely directly penetrating proton is shown that had an initial energy of 45 MeV and an initial pitch angle of 85° (Fig. 3.77). It was launched at simulation time 6 h and 45 min. It had a huge Larmor radius in the solar wind that tightened as it crossed the bow shock and magnetopause. This particle moved easily between different field line types until it struck the inner boundary. It experienced $\kappa < 2$ throughout much of its time in the magnetosphere.

3.16.11 Demonstration of the Magnetospheric Configuration's Control of the Entry of High-Energy Particles

One way to demonstrate the magnetospheric configuration's control of the entry of high-energy particles is to plot the population of the inner magnetosphere and the precipitation rate (Fig. 3.78) as a function of time.

The numbers in Fig. 3.78 were computed assuming that the upstream flux represents a total flux above 100 keV of 2.5×10^8 protons/m².sec. This number is based on the differential flux for a typical SEP event at 100 keV taken from Gloeckler (1984). The precipitation rate, i.e., precipitation onto the inner boundary at 4.5 $r_{\rm E}$, shows a fairly systematic variation with IMF. Recall that the IMF was southward at first, then dawnward, and finally northward. Also bear in mind that part of the flux in the polar cap on open field lines that do not connect to the dayside has been omitted. During southward IMF the precipitation rate was relatively high, reflecting an abundance of open field lines and efficient transport into the inner magnetosphere. The rate decreased during the dawnward IMF interval and finally fell to a very low level during steady northward IMF. The trend is consistent with the decrease of open field lines that occurred as the IMF changed from northward to southward, as shown in Fig. 3.65.

The number of protons at less than $7r_E$ (Fig. 3.78) can be taken to reflect the population of the inner magnetosphere in the model. While some of these protons were quasi-trapped in the inner magnetosphere, most of them remained only briefly in the inner magnetosphere before reaching the inner boundary or exiting the system, usually tailward or duskward. Only about 1% of the test protons remained in the inner magnetosphere for more than 15 min. Some protons were observed to make a nearly complete circle around the earth, then exit back into the magnetosheath. The initial increase of the population during southward IMF was evidently due to the system filling with protons as the calculation proceeded; particles could take a few minutes to reach this region. During southward IMF, most protons entered the inner magnetosphere on the dayside. After the IMF turned dawnward, the number entering the inner magnetosphere on the dayside decreased and highest concentration



Fig. 3.77 Proton trajectory is shaded gray according to field line type and points along a particle trajectory projected onto the z = 0 (*top* panel), y = 0 (*middle* panel), and x = 0 (*bottom* panel) planes are shown. Points where the particle was on open field lines are light gray, ones on closed field lines are dark gray, and ones on solar wind field lines are medium gray. Filled circles indicate local minima of κ where $\kappa < 2$ that were more than 1.6 $r_{\rm E}$ apart (From Richard et al., 2002)



Fig. 3.78 Precipitation rate and population of the inner magnetosphere as a function of time. The gray bands indicate the times when the IMF was changing. The top panel shows the precipitation rate onto the inner boundary of the simulation for an upstream flux of 2.5×10^8 protons m⁻² sec⁻¹. Data points are 15 min apart. The bottom panel shows the number of particles between 7 r_E and the inner boundary for the same upstream flux, with data points every 5 min (From Richard et al., 2002)

of arrival points (into the inner magnetosphere) was found dawnward of midnight. Evidently these were particles that entered the magnetotail on the dawn-side open field lines and reached the inner magnetosphere. The overall population in the inner magnetosphere decreased during dawnward IMF as the region of particle arrival moved tailward. As the IMF changed to northward, the entry rate into the inner magnetosphere increased again, with protons arriving primarily from the dawn side. During this transition, the number of particles in the inner magnetosphere increased, but this is due to the particles in the southern cusp, not trapped or quasi-trapped particles. As steady northward IMF conditions continued, few particles reached the inner magnetosphere with most of these briefly entering near the southern cusp.

3.16.12 On the ³He Ion Trajectories for Southward IMF

The ³He ion abundance is enhanced during impulsive SEP events. Richard et al. (2002) calculated ³He ion trajectories for southward IMF only. The flux distribution for these particles was qualitatively similar to that of the protons that are shown in Fig. 3.67, but the fluxes within the magnetosphere were reduced relative to the upstream flux. For the purpose of comparison with protons, Richard et al. (2002) plotted the population of the inner magnetosphere and precipitation for these particles in Fig. 3.78 as if they had the same upstream flux as the protons. It can be seen that they entered the inner magnetosphere and precipitated at a lower rate (relative to their upstream flux) than the protons. This is consistent with the role of κ in particle entry. For particles of the same energy, the velocity of a proton will be greater than that of an ³He ion by a factor of the square root of the mass ratio. The mass of a ³He ion is three times the mass of a proton while the charge doubles. This leads to a proton having a Larmor radius 15% larger than a ³He ion of the same energy.

3.16.13 Main Results and Discussion

Richard et al. (2002) have shown that in their trajectory calculations, high-energy particles' access to the magnetosphere was strongly controlled by the IMF. For a steady proton source, the omni-directional proton fluxes in some locations in the magnetotail varied by a factor of 100 as the IMF changed. Transport into the inner magnetosphere varied by a factor of 5. A southward IMF condition allowed the greatest access to the magnetosphere of the IMF conditions studied, dawnward IMF less, and northward IMF considerably less. The cusp was an important entry region for the high-energy particles for northward and southward IMF, while the dawn-side flank was the dominant entry location for dawnward IMF. Fritz et al. (1999) reported that energetic particles are frequently observed in the cusp region. While they have ruled out an SEP source for events seen on August 27, 1996 it is possible that some of these events are related to SEPs. Relative to their initial high energy, the SEPs in above described calculations usually did not gain or lose much energy. The exceptions were particles that remained trapped long enough to gain or lose energy adiabatically during IMF transitions. It was likely that because of the inner boundary at $4.5 r_{\rm E}$, some particles that otherwise would remain trapped and possibly further energized, are lost. It may be easy to estimate this energization. In being transported from $6r_E$ to $4r_E$ at midnight, an equatorial pitch angle particle conserving μ would increase in energy by a factor of 2.8. The transport of SEPs in these calculations often involved non-adiabatic motion. Particles usually entered the magnetosphere while they were not adiabatic. Non-adiabatic motion could also be important for the transport of particles onto trapped or quasi-trapped paths.

Time-independent calculations gave results that were quite similar to the timedependent ones in the outer magnetosphere, even though the latter were obtained by accumulating data through half an hour to an hour, while the magnetosphere was slowly varying. This indicates that for a slowly varying magnetosphere, a time-independent calculation is adequate for modeling energetic particle entry. This can be attributed to the fact that high-energy particles rapidly precipitated became trapped or exited the magnetosphere. There were hints that particle penetration was enhanced in the time-dependent case, suggesting that a rapidly varying magnetosphere could experience significantly enhanced particle penetration. On the other hand, trapped particles experienced the consequences of IMF changes. These particles, however, remained a minor part of the total population in the inner magnetosphere during southward and dawnward IMF. The trapped particles were affected by IMF changes largely through adiabatic changes that affected the particle orbits by a relatively small amount and changed their energies. During northward IMF, when particles from the solar wind did not become trapped, the trapped particle population consisted solely of particles that had entered the magnetosphere during earlier IMF orientations. The population of trapped particles was reduced in our calculation, however, by the removal of particles at $4.5 r_{e}$ from the earth.

Because IMF conditions typically undergo much more rapid variations than in this idealized case, particle entry into the magnetosphere may be even more complex than in our results. In this calculation the residence time of the vast majority particles in the magnetosphere was much less than the duration of transitions in the IMF (half an hour). For rapid variations in the IMF, especially when a shock strikes the magnetosphere, the entry process would probably be modified. Richard et al. (2002) argued that if the SEP proton flux in the solar wind during an intense gradual proton event could easily enter the magnetosphere, it would dominate the plasma sheet population in the energy range above 0.1 MeV. Their model indicates that the SEP flux within the magnetosphere does become comparable to the solar wind flux in parts of the magnetosphere depending on IMF orientation. The near-earth magnetotail under southward IMF is one instance of this.

3.17 Propagation of Protons in the Energy Range 0.1–50 MeV through the Earth's Bow Shock, MagnetoSheath, and Magnetopause Inside the Magnetosphere

3.17.1 The Matter of Problem

Shimazu and Tanaka (2005) note that researchers have long studied the questions of how SEPs reach the earth and how they move in the earth's magnetic field. Early results revealed that relatively low-energy SEPs access only high latitudes in the atmosphere. In the case of the dipole magnetic field, the lowest accessible latitude on the earth is called the Störmer cutoff latitude. In the 1960s and 1970s, comparisons of satellite observations and calculations of particle trajectories based on models of the earth's magnetic field clarified how SEPs enter the magnetosphere and how

they move in the earth's magnetic field (Morfill and Scholer, 1973). In these trajectory calculations, static models were used for the electric and magnetic fields. In the 1990s, progress was made in global MHD simulations of the interaction between the solar wind and the magnetosphere. These simulations can reproduce realistic electric and magnetic fields in the magnetosphere. Thus the entry of SEPs into the magnetosphere and their trajectories can be studied by using simulation data that take the configuration of the magnetosphere into account. Richard et al. (2002) simulated SEP entry into the magnetosphere by using global MHD simulation data (see above, Section 3.16). They showed that more protons can reach the inner magnetosphere when the IMF has a southward component. Kress et al. (2004) traced protons from the earth's ionosphere in reverse and showed that the cutoff latitude for 25 MeV protons becomes low when the dynamic pressure of the solar wind increases.

SEPs observed near the earth are manifestations of particle acceleration in the Heliosphere. They are considered to derive from two different sources (Reames, 1999): (1) solar flares, and (2) shock waves driven outward from the sun by coronal mass ejections (CMEs). The intensity-time profiles of SEPs observed by a satellite near the earth can be distinguished from one another. Solar flares cause impulsive ³He-rich events. In contrast, shock waves driven by CME cause gradual proton events, in which the observed proton flux increases slowly as compared with an impulsive event.

Shimazu and Tanaka (2005) note that the access of SEPs to the earth is not only an interesting topic in geophysics but also a problem of practical importance from the viewpoint of space weather. Protons arriving at low altitudes ionize neutral atoms in the E and D layers of the ionosphere (i.e., they cause impact ionization). One consequence of the increased ionization of the high-latitude ionosphere is polar cap absorption (PCA) (Bailey, 1964; see also in Velinov et al., M1974, and in Dorman, M2004), which adversely affects airplane communications using high-frequency (HF) radio waves. These protons also represent a serious threat to electrical components onboard spacecraft in high-inclination orbits.

3.17.2 Three Categories of Energetic Protons Incoming to the Earth

Shimazu and Tanaka (2005) classify protons incoming to the earth into three categories, depending on the interaction process with the magnetosphere. The first category is low-energy protons (less than 100 keV). These are thermal protons forming a component of the solar wind and carrying the MHD flow. The second category is high-energy protons (greater than 50 MeV). These protons are not much affected by the earth's magnetic field because their cyclotron radii are greater than the scale of the magnetosphere. The last category, which is considered in detail in the paper of Shimazu and Tanaka (2005), are protons in the energy range between 100 keV and 50 MeV. These protons trajectories are affected by the electric and magnetic fields in the magnetosphere because their cyclotron radii are less than or comparable to its scale. Since the flux of these protons is much lower than that of the thermal protons, it is not necessary to consider feedback from the electric current that they generate. Therefore it is reasonable to calculate the trajectories of protons in this category in given electric and magnetic fields. Shimazu and Tanaka (2005) investigated energetic proton propagation through the earth's bow shock, magnetosheath, magnetopause, and magnetosphere from the upstream side of the solar wind by integrating particle orbits according to data from previous global MHD simulation (Tanaka, 1995, 2000). Utilizing the simulation data enabled considering the dynamic response of protons in realistic electric and magnetic fields in the magnetosphere. Shimazu and Tanaka (2005) specifically considered protons in the energy range from 100 keV to 10 MeV. So far, little attention has been paid to the questions of whether solar protons in this energy range are accelerated near the earth and whether their acceleration is related to how they enter the magnetosphere.

3.17.3 Energetic Proton Propagation through Bow Shock with Shock-Drift Acceleration

One of the possible mechanisms for this acceleration is shock-drift acceleration at the collisionless fast-mode bow shock (the mechanism of shock-drift acceleration was first supposed and developed in Dorman and Freidman, 1959; see detail in Chapter 4 in Dorman, M2006). Since the downstream value of the magnetic field in the fast MHD shock waves is greater than the upstream value, the shock front acts as a magnetic mirror reflecting some incident particles. The reflected particles move along the shock front through the gradient-B drift. Since the direction of the gradient-B drift agrees with the direction of the acceleration due to the electric field in the shock frame, the particles gain energy through this process. When the particles' cyclotron radii are less than the scale of the shock curvature or structure, the particles can cross the shock every cyclotron period and gain significant energy in the drift. The shock-drift acceleration has been considered theoretically in the de Hoffmann-Teller frame of reference, in which the electric fields vanish on both sides of the shock, because each particle's energy is conserved in this frame (Decker, 1988). The de Hoffmann–Teller frame, however, is more suitable for investigating a planar shock. Here, because are considered a curved bow shock and focus on proton entry into the magnetosphere, there instead use the GSM coordinates (the frame moving with the earth) to express the velocity and the electric field.

The shock-drift mechanism has been intensively studied. Observational evidence was presented by Blokh et al. (1959), Anagnostopoulos and Sarris (1983), and Anagnostopoulos and Kaliabetsos (1994), while theoretical descriptions were given by Dorman and Freidman (1959), Dorman (1959), Shabansky (1961), Sonnerup (1969), Terasawa (1979), Decker (1988), and Giacalone (1992) for protons and by Vandas (2001) for electrons. So far, however, only a few attempts have been made at examining the relation between the acceleration and the entry into the magne-

tosphere. Shimazu and Tanaka (2005) intend this research as an investigation of the energies of protons entering the magnetosphere and the relation between their entry and the shock-drift acceleration.

3.17.4 Energetic Particles Propagation through Bow-Shock with Diffusive Shock Acceleration

The other possible mechanism for proton acceleration is diffusive-shock (first-order Fermi) acceleration (see detail in Chapter 4 in Dorman, M2006). This process is especially effective at a quasi-parallel shock, where small-scale turbulence scatters particles (Scholer, 1990). Particle acceleration has also been considered as a result of scattering by large-amplitude waves (Kuramitsu and Hada, 2000). Strictly speaking, with the inclusion of particle scattering, the mechanism referred to as shock-drift acceleration is a subset of the more general diffusive shock acceleration. However, MHD simulations do not account for small-scale turbulence within the shock transition region and upstream waves (at a scale less than the grid size), which significantly affect the motion of particles. It is necessary to introduce a scattering timescale in order to include these effects in the simulation. Though this is an interesting topic, Shimazu and Tanaka (2005) do not focus on small-scale turbulence in the described research. Rather, to distinguish scatter-free acceleration from diffusive acceleration induced by small-scale turbulence, it is important to first clarify the effect of scatter-free shock-drift acceleration on proton entry into the magnetosphere. They follow the latter approach in this research.

3.17.5 MHD Simulation

Shimazu and Tanaka (2005) first performed a global MHD simulation of the interaction between the solar wind and the earth's magnetosphere (Tanaka, 1995). We solved the MHD equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \qquad (3.161)$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho \left(\mathbf{v} \cdot \nabla \right) \mathbf{v} = -\nabla P + \frac{1}{\mu} \left(\nabla \times \mathbf{B} \right) \times \mathbf{B}, \qquad (3.162)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \qquad (3.163)$$

$$\frac{\partial U}{\partial t} + \nabla \cdot \left(\mathbf{v} \left(U + \frac{B^2}{2\mu} + P \right) - \frac{\mathbf{B} \left(\mathbf{v} \cdot \mathbf{B} \right)}{\mu} \right) = 0, \qquad (3.164)$$

where

$$U = \frac{P}{\gamma - 1} + \frac{\rho v^2}{2} + \frac{B^2}{2\mu},$$
(3.165)

and ρ is the density, *t* is time, *v* is the velocity, *P* is the pressure, μ is the permeability, *B* is the magnetic field, and γ is the polytrophic index.

In this simulation, Shimazu and Tanaka (2005) applied a third-order TVD scheme based on the monotonic upstream scheme with a linearized Riemann solver. They assumed a uniform solar wind at the upstream boundary and a zero gradient at the downstream boundary. Then they included the dipole magnetic field (potential field) in the simulation. The inner boundary (at $3r_E$) was regarded as the ionosphere. The ionospheric potential was solved to match the divergence of the Pedersen and Hall currents with the field-aligned current. The electrical conductivity of the ionosphere depends on the solar zenith angle and the magnitude of the field-aligned current. In this study, the same values were used for these ionospheric conductivity parameters as in Tanaka (2000). In examining the magnetosphere-ionosphere coupling process, numerical errors in the low-pressure region near the ionosphere should be reduced. For this purpose, the MHD calculation was reconfigured so as to suppress the direct inclusion of the magnetic field's potential component as a dependent variable. A system of equations incorporating such a modification can still be written in a conserved form and can be treated by the TVD scheme. Through this scheme, Tanaka (1995, 2000) advanced the understanding of the field-aligned current system in the magnetosphere, of the structure and origin of the magnetospheric convection, and of the sub-storm mechanism in relation with the convection.

3.17.6 The Grid System for Simulation

Shimazu and Tanaka (2005) utilized a grid system based on the modified spherical coordinates (Tanaka, 2000). This grid system gives coarse meshes in the solar wind region, and fine meshes near the inner boundary and in the plasma sheet region. Therefore, it is suitable for investigating the interaction between the solar wind and the magnetosphere. The numbers of grid points were 56, 58, and 40 in the r, q, and f directions, respectively. The MHD simulation model was symmetric with respect to the equatorial plane because we did not include the dipole tilt. The velocity of the solar wind and the components of the IMF were set to $v_{sw} = 450 \text{ km/s}$, $B_x = 0$, $B_y = -2.5 \text{ nT}$, and $B_z = 4.2 \text{ nT}$, respectively, as typical parameter values. The time step was 0.06 sec, and the electric and magnetic field data were saved every 6 sec.

3.17.7 The Efficiency of the Shock-Drift Acceleration

To investigate the efficiency of the shock-drift acceleration, Shimazu and Tanaka (2005) increased the dynamic pressure of the solar wind in the simulation runs. To

exclude the effect of the electric field, they considered a density increase, rather than a velocity increase, as a dynamic pressure increase. Here, they considered the situation in which there is a density increase (i.e., an interplanetary shock) at the magnetopause after the SEP has already arrived there. This situation is often observed because an interplanetary shock, which can be a source of SEPs, propagates slower than do the SEPs. In the simulation, the solar wind density was increased from 10 cm^{-3} to 30 cm^{-3} (case A) and to 100 cm^{-3} (case B), at $x = 30 r_{\text{E}}$ on the upstream side, from t = 0 to t = 1 min. This density change then arrived at the subsolar bow shock ($x \approx 12 r_{\text{E}}$) at around t = 4.3 min and at the sub-solar magnetopause ($x \approx 10 r_{\text{E}}$) at around t = 4.7 min.

3.17.8 Calculation of Proton Trajectories for Three Regions

The proton trajectories in Shimazu and Tanaka (2005) were calculated using the electric and magnetic field data from the MHD simulation. Since B_x was 0, Shimazu and Tanaka (2005) injected protons on the upstream side of the solar wind surrounding the magnetosphere in the following regions: (1) $0 < x/r_E < 30$, $0 < y/r_E < 30$, $28 < |z|/r_E < 30$; (2) $0 < x/r_E < 30$, $28 < |y|/r_E < 30$, $0 < z/r_E < 30$; and (3) $28 < x/r_E < 30$, $-30 < y/r_E < 30$, $-30 < z/r_E < 30$ (shown by the white areas in Fig. 3.79). The protons were injected when 30 min of real time had passed from the start of the MHD simulation run. This time corresponded to t = -5 min. This 30-min period was the duration required for the MHD simulation to reach an equilibrium state. The protons were isotropic and were injected at a constant rate, with various pitch angles.

To calculate the proton trajectories, Shimazu and Tanaka (2005) solved the equation of motion for protons which included the relativistic effect:

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{m\mathbf{v}_p}{\left(1-\left(v_p/c\right)^2\right)}\right) = e\left(\mathbf{E} + \mathbf{v}_p \times \mathbf{B}\right),\tag{3.166}$$

where *m* is the proton mass, \mathbf{v}_p is the proton velocity, *c* is the speed of light, *e* is the unit charge, and E is the electric field, which equals $-\mathbf{v} \times \mathbf{B}$. Equation 3.166 was integrated numerically. The time step was 0.01 sec. In the simulation the nearest grid point to each proton was searched for. Then, the electric and magnetic fields at a proton's location were interpolated from the values at the neighboring grid points according to the distances between the location and the grid points. The inner boundary for the trajectory calculation was set to $4r_{\rm E}$, while the outer boundary was set to $70r_{\rm E}$.

3.17.9 Results for the Shock-Drift Acceleration at the Bow Shock (Case A)

As a starting point, Shimazu and Tanaka (2005) considered the case where the density of the solar wind increased from 10 to 30 cm^{-3} (case A). These values correspond to a dynamic pressure increase approximately from 3.4 to 10 nPa. The z component of the IMF (B_z) was set to be positive to distinguish the effect of negative B_z from that of the dynamic pressure increase. Figure 3.79 shows the distribution of the pressure on the noon–midnight meridian plane around the earth, as calculated in the MHD simulation. When the solar wind density increase arrived, the pressure increased on the downstream side of the bow shock in the magnetosheath. As this pressure increase propagated to the downstream side in the magnetosheath, the



Fig. 3.79 Pressure distribution on the noon–midnight meridian plane around the earth as calculated in the MHD simulation (case A) at t = 0.0 min (panel **a**), 6.0 min **b**, 8.0 min **c**, and 10.0 min **d**. The radius of the black circle at the center is 4 r_E . The white areas are the locations of the initial proton injections. The curves in panels **c** and **d** represent the dayside region at 9 r_E , where the spectra and pitch angles shown in Figs. 3.80 and 3.81 are calculated (From Shimazu and Tanaka, 2005)





magnetosphere on the dayside was compressed. The details of the magnetosphere changes obtained using the same MHD code can be found in the work of Fujita et al. (2003a, b).

To determine whether the shock-drift acceleration could be observed in this simulation, Shimazu and Tanaka (2005) plotted the energies and pitch angles of the protons. Figure 3.80 depicts the energy spectra for the protons in the initial population and on the downstream side of the shock after the density increase arrived ($t \sim 6-10$ min).

The initial spectrum is for the upstream population and does not include protons reflected at the shock. The spectrum on the downstream side was obtained by integrating the protons over the dayside at $9r_E$. This location is in the magnetosheath, as shown by the curves in panels c and d of Fig. 3.79. Only the protons coming from farther than $9r_E$ are counted (i.e., the inward proton flux from the upstream side), while those coming back from the magnetosphere were not included. As a result, Shimazu and Tanaka (2005) did not need to consider the effect of the magnetopause here. They set the initial incident spectrum as a κ distribution (Christon et al., 1988) determined by Eq. 3.160 (see in Section 3.16) with a κ coefficient of 0.5, where *E* is the particle energy and E_T is the thermal energy which was set to 40 keV here. As noted above, the energy range of the injected protons was from 100 keV to 10 MeV.

Figure 3.80 shows that the spectrum became harder on the downstream side. The initial flux was proportional to $E^{-1.46}$, and on the downstream side, the flux of protons in the energy range between 700 keV and 4 MeV was proportional to $E^{-1.27}$. Note that this does not indicate only shock-drift acceleration but may also include the energy-dependence on the particle transmission rate through the shock. In contrast, the spectrum index above 5 MeV on the downstream side was almost the same as that of the initial one. The downstream spectrum also appears almost parallel to the initial one at intermediate energies (300–700 keV). This is additional evidence for the shock-drift acceleration (Decker, 1983; Anagnostopoulos and Kaliabetsos, 1994).





Figure 3.81 shows the pitch-angle distribution integrated over the northern hemisphere on the dayside at $9r_{\rm E}$ after the density increase arrived ($t \sim 6-10$ min).

Shimazu and Tanaka (2005) also considered only the inward proton flux here. The energies of the upstream protons were set to be monochromatic (100 keV) to ensure comparability with the previous results. The distribution shows the same characteristic signature for the transmitted protons after the shock-drift acceleration as that shown by Giacalone (1992). Transmitted 100 keV protons exhibit a peak at around 45° as a result of the shock-drift acceleration at a curved shock (Giacalone, 1992). Therefore, the results shown in Fig. 3.81 suggest the presence of shock-drift acceleration.

3.17.10 Energetic Particle Entry into the Magnetosphere and Expected Polar Map of Proton Precipitation at $4r_e$ (Case A)

Shimazu and Tanaka (2005) recorded the protons that had energies of 10 MeV at the moment of injection and reached the inner boundary at 4 RE before the solar wind density increase ($t \sim 1-4$ min). Then, they plotted the locations where the protons reached $4r_{\rm E}$, as shown in Fig. 3.82.

Figure 3.82 thus represents the polar map of proton precipitation at $4r_E$. Shimazu and Tanaka (2005) intend this figure to represent a statistical and complete image of proton entry into the magnetosphere, before discussing the trajectories of individual protons. Figure 3.82 shows all protons that reached $4r_E$. The locations were not distributed uniformly in latitude but were instead localized at high latitudes (greater than 43.6°). The results indicate that the trajectories were affected by the earth's magnetic field. Tracing the proton that reached the lowest latitude, along the dipole magnetic field line, we observed that it reached 68.1° of latitude at $1r_E$, which corresponds to the cutoff latitude.



Fig. 3.82 Locations where 10 MeV protons reached 4 $r_{\rm E}$, before the solar wind density increase $(t \sim 1-4 \text{ min})$, shown by a polar map. The figure shows a superposition of the northern and southern hemispheres over 30° of latitude. The latitude lines for 30°, 40°, 50°, 60°, 70°, and 80° and longitude lines for 00, 06, 12, and 18 h local time (LT) are shown (From Shimazu and Tanaka, 2005)

Previous studies described in Section 3.16 have shown that protons enter the magnetosphere easily from open field lines, where the earth's magnetic field lines reconnect with interplanetary magnetic field lines, when the IMF has a southward component (Richard et al., 2002). In the case examined here, the IMF had a northward component, but most of the protons that entered the magnetosphere moved over the cusp region, where the magnetic field was relatively weak. Some of these protons reached high latitudes on the dayside. Most of the protons that reached the nightside also entered the magnetosphere at a high altitude over the cusp region, but they crossed field lines and became trapped by the earth's magnetic field. They then bounced and drifted from the dawn side to the nightside (i.e., gradient drift). They gained or lost energy adiabatically while trapped in the magnetic field, and some of them precipitated on the nightside.

There was little proton flux on the nightside of the polar region, as shown in Fig. 3.82. Tracing 10 MeV protons in reverse from the nightside of the polar region, we found that they came from the far magnetotail. Since Shimazu and Tanaka (2005) did not include protons from the tail in this simulation, there was little proton flux in this region. These protons from the far tail are known to exhibit delayed entry into the magnetotail (Van Allen et al., 1987).
3.17.11 Relation Between Proton Entry and Shock-Drift Acceleration

Figure 3.83 shows a time profile of the latitudes and energies at which protons reached $4r_{\rm F}$. Shimazu and Tanaka (2005) examined three initial monochromatic energy cases, 100 keV, 1 MeV, and 10 MeV, which enabled them to study the dependence of the entry flux and the cutoff latitude on the energy. As described above, the solar wind density increase arrived at the sub-solar bow shock at around t = 4.3 min and at the sub-solar magnetopause at around t = 4.7 min. Shimazu and Tanaka (2005) found that the proton flux at $4r_{\rm E}$ increased after the density increase arrived. In particular, almost no 100 keV protons arrived before the density increase, but afterward they did reach $4r_E$ (panel **a** in Fig. 3.83). For both 1 MeV and 10 MeV protons, the lowest latitude that the protons could reach became lower after the density increase than it had been before (panels b and c in Fig. 3.83), which agrees with the results given by Kress et al. (2004). The flux of 10 MeV-protons was higher than that of 1 MeV protons, because Shimazu and Tanaka (2005) did not apply a realistic spectrum (i.e., a power law) on the upstream side. Note that in real interplanetary space, the 10 MeV flux is much less than the 1 MeV fluxes. A remarkable finding here was the acceleration of the 100 keV protons. Some of these protons were ac-



Fig. 3.83 Time profiles of the latitudes (panels **a**, **c**, and **e**) and energies (**b**, **d**, and **f**) of protons reaching 4 r_E in case A, for energies of 100 keV (**a** and **b**), 1 MeV (**c** and **d**), and 10 MeV (**e** and **f**) at the moment of injection (From Shimazu and Tanaka, 2005)



Fig. 3.84 Time profile of the energy of initial 100 keV proton during the shock-drift acceleration. The time period of shock-drift acceleration (t = 6.6-7.4 min) is indicated by the bars on the horizontal axes (From Shimazu and Tanaka, 2005)

celerated to energies three times higher than on the upstream side. In contrast, none of the 1 MeV or 10 MeV protons were accelerated to energies even twice as high.

Figure 3.84 shows an example of a time profile for the energy of a 100 keV proton.

The profile in Fig. 3.84 indicates that the proton's energy increased rapidly from t = 6.6 to t = 7.4 min.

Figure 3.85 illustrates the trajectory of the same proton. The white lines represent the trajectory, and the grey code represents they component of the electric field *E* at t = 7.0 min. They component predominated over the other components of the electric field. The black lines denote the location of the bow shock, which was determined from the pressure distribution. This trajectory shows that the proton drifted along the bow shock when its energy increased (shown by the black lines for time t = 6.6-7.4 min). The grey code given in Fig. 3.85 illustrates that E_y observed in the frame moving with the earth was amplified to approximately 5 mV/m over the cusp region in the magnetosheath at t = 7 min. This value is consistent with the electric field observed where shock-drift acceleration of protons occurred (Anagnostopoulos and Kaliabetsos, 1994).

The reason for the enhancement over the cusp region was the combination of the magnetosheath flow v_x and the piled-up B_z . After the proton was accelerated at the bow shock, it entered the magnetosphere at a high altitude over the cusp region. Finally, it was trapped by the earth's magnetic field, drifted from the dawn side to the nightside, and reached the inner boundary on the nightside.

It can be concluded from the proton's trajectory analysis that the proton was accelerated at the bow shock through the shock-drift mechanism. Since B_x was 0, the entire bow shock simulated here was almost quasi-perpendicular. The magnetopause is one candidate for providing this acceleration, but the electric field there was not as large as that on the downstream side of the shock, as illustrated in Fig. 3.85. The detailed analysis of other proton trajectories in the simulation also showed that the energy changes in other places were much smaller than that at the bow shock.



Fig. 3.85 Trajectory of the same proton as shown in Fig. 3.84, indicated by the white lines, with the black lines representing the part of the trajectory from t = 6.6 to t = 7.4 min. The trajectory is projected onto **a** the $z = 3 r_{\rm E}$ plane, **b** the $y = 6 r_{\rm E}$ plane, and **c** the $x = 6 r_{\rm E}$ plane. The grey code at the right represents electric field E_y at t = 7 min for case A. The black lines denote the location of the bow shock (From Shimazu and Tanaka, 2005)

3.17.12 Statistical Results for Proton Entry and Shock-Drift Acceleration

It was shown above that shock-drift acceleration was effective for the single protons. Since higher-energy protons have higher probabilities of entering the magnetosphere and can reach lower latitudes, in general, the shock-drift acceleration can account for part of the variation in the precipitation flux and the cutoff latitude after the density increase arrived, as shown in Fig. 3.83. Correlation of the precipitation flux increase with the arrival of the density increase strongly suggests this. Thus, it seems reasonable to suppose that the role of the shock-drift acceleration in proton entry into the magnetosphere is to increase the proton flux into the magnetosphere and lower the cutoff latitude. In addition to the proton acceleration, it was pointed out that the compression of the magnetosphere due to a dynamic pressure increase also has the effect of lowering the cutoff latitude (Obayashi, 1961). Therefore, these two factors contributed to lowering the cutoff latitude shown in Fig. 3.83.

3.17.13 Results for Large Solar Wind Density Increase (Case B)

It follows from the above results that higher-energy protons can be accelerated if the solar wind density increases further. We thus also simulated a case in which the solar wind density was increased from 10 to 100 cm^{-3} (case B), corresponding to a dynamic pressure increase approximately from 3.4 to 34 nPa. Figure 3.86 depicts the energies of protons that reached $4r_{\text{E}}$ in this case. The energies of the upstream protons were monochromatic, 100 keV, 1 MeV, and 10 MeV. The maximum energy of the 100 keV protons increased with time, as shown in Fig. 3.86 (panel a). The statistical energy increase observed in Fig. 3.86 (panel a) was mostly caused by the pressure increase (i.e., the increase in the electric field) in the magnetosheath at that time (from t = 6 to t = 10 min), as shown in Fig. 3.79 (panels c and d). Figure 3.86 (panel b) shows that some 1 MeV protons at the moment of injection were accelerated to more than 2 MeV after the density increase arrived. Comparing Fig. 3.83 and Fig. 3.86 shows that not only the 100 keV protons but also the 1 MeV protons could be accelerated in this case.

3.17.14 Comparison Between Cases A and B

From Fig. 3.86 (panel c) it can be seen that for some 10 MeV protons, their energies reached 12 MeV. Among these protons, however, none were accelerated to twice the energy, unlike 1 MeV protons. The acceleration capability thus constituted 1 or 2 MeV in case B, which was much higher than the order of 100 keV for case A. The difference between cases A and B was the electric field magnitude on the down-



Fig. 3.86 Time profiles of the energies of protons reaching 4 r_E in case B, for energies of **a** 100 keV, **b** 1 MeV, and **c** 10 MeV at the moment of injection (From Shimazu and Tanaka, 2005)

stream side of the shock. As estimated from the results of the MHD simulation, the electric field in the magnetosheath over the cusp region for case B was approximately 15 mV/m, or three times as large as that for case A, after the density increase passed. A comparison between cases A and B indicated that the electric field on the downstream side of the shock is the key element in determining the shock-drift acceleration at the bow shock when the solar wind density increased.

3.17.15 Discussion on the Main Results and Observational Evidence

The main results of the above-described research of Shimazu and Tanaka (2005) are as follows:

When the solar wind density did not change, 100 keV protons could not reach $4r_{\rm E}$.

In case A, the solar wind density increased from 10 to 30 cm^{-3} , which often happens in reality. In this case, 100 keV protons could be accelerated through the shock-drift mechanism at the bow shock and reached $4r_{\text{E}}$.

In case B, the solar wind density increased from $10 \text{ to } 100 \text{ cm}^{-3}$. In this case, the obtained results indicated that shock-drift acceleration of 1 MeV protons is possible at the Earth's bow shock, although such a significant density increase does not often occur.

Other physical parameters, however, can also provide appropriate conditions for proton acceleration in the energy range above 1 MeV. These parameters include the solar wind velocity, the IMF, the ratio of the upstream magnetic field to the downstream magnetic field, and the ratio of the proton cyclotron radius to the local radius of the shock curvature, or a combination of these parameters.

The observational evidence on the reality of the above-described simulations was obtained in different experiments. In fact, Anagnostopoulos and Kaliabetsos (1994) found from IMP 8 and IMP 7 data that protons were accelerated up to energies as high as 4 MeV in the vicinity of the quasi-perpendicular bow shock when a sudden commencement of geomagnetic storm occurred. At the time of the observation, the magnitude of the IMF was 10-30 nT, which is more than twice the value used in the described simulations. Thus, the observation of the proton acceleration in the energy range greater than 1 MeV seems reasonable from the viewpoint of the simulation. Although the values of the parameters were not exactly the same, the shock-drift acceleration of solar protons up to energies in the order of 1 MeV is not only a theoretical possibility but has actually been observed. The simulation results indicated that the electric field on the downstream side was not transient. Since a 100 keV proton travels $41 r_E$ in 1 min, the electric field on a timescale longer than 1 min is not transient for such a proton. The enhanced electric field over the cusp region in the magnetosheath had a timescale longer than 1 min. Instead of a transient field, an almost steady, enhanced electric field on the downstream side contributed to the acceleration. Thus betatron acceleration cannot be the main acceleration mechanism here.

Shimazu and Tanaka (2005) have confined attention to the case where the *x* component of the IMF (B_x) is 0. If B_x is not 0, the bow shock has a quasi-parallel configuration where shock-drift acceleration would not occur. Rather, diffusive-shock acceleration is known to occur at a quasi-parallel shock, as was noted above. Protons can also be scattered and accelerated by turbulence in the magnetosphere, the bow shock, and the foreshock region. Ion-cyclotron waves in the outer part of the

Earth's magnetosphere can also accelerate protons. In the progress of this important research, the effects of small-scale turbulence on the proton acceleration will be included.

Shimazu and Tanaka (2005) have examined how the shock-drift acceleration at the Earth's bow shock affects the entry of solar energetic protons into the magnetosphere. The paper describes the results of the first simulation combining the shock-drift acceleration and proton entry into the magnetosphere. Through this simulation, the trajectories of protons were traced in the energy range from 100 keV to 10 MeV from the upstream side of the solar wind, in electric and magnetic fields obtained from global MHD simulation data. The results showed that the proton flux entering the magnetosphere was increased and that the cutoff latitude became lower when the dynamic pressure of the solar wind was increased. Under quiet solar wind conditions in this simulation, 100 keV protons could not reach $4r_{\text{E}}$. Protons entering the magnetosphere, reaching $4r_{\rm E}$, and having energies in the orders of 100 keV and 1 MeV could experience shock-drift acceleration at a quasi-perpendicular bow shock, when the solar wind density increased. In fact, the shock-drift acceleration of solar protons up to energies as high as 4 MeV was actually observed by spacecraft. The effects of the shock-drift acceleration on proton entry into the magnetosphere were to increase the proton flux into the magnetosphere and to lower the cutoff latitude. Compression of the magnetosphere also contributed to lowering the cutoff latitude, in addition to the proton acceleration, when the dynamic pressure increased. Protons entered the magnetosphere mainly at a high altitude over the cusp region, where the magnetic field was relatively weak, even when B_z was positive. These protons could reach lower latitudes because they were accelerated and the magnetosphere on the dayside was compressed. A comparison between the cases of high and low dynamic pressure showed that the enhanced electric field on the downstream side of the shock in a frame of reference moving with the Earth was the key element in determining the trajectory.

Shimazu and Tanaka (2005) have shown the importance of energetic particle traces in the shock-drift acceleration at the Earth's bow shock. To conduct this research, information on the electric and magnetic fields over a wide area around the Earth and in the solar wind is necessary. If this information is obtained, it will be possible to compare simulations and observations conducted under almost the same actual conditions. MHD simulation suits this purpose, and combining it with energetic particle traces will facilitate development of research on particle acceleration in the actual configuration of the magnetosphere.

Chapter 4 Cosmic Ray Planetary Surveys on Ships, Trains, Tracks, Planes, Balloons, and Satellites

4.1 CR Latitude Surveys by Japanese Expeditions during 1956–1962 to Antarctica on the Ship Soya

4.1.1 The Routes and CR Apparatus in Japanese and Some Previous Latitude Surveys

Within the framework of the project "Japanese Antarctic Research Expedition," measurements were taken of CR intensities (nucleonic – by a Simpson-type neutron monitor described in Simpson (1951), and muonic – by a Neher-type ionization chamber which was used in previous Japanese expeditions by Sekido et al., 1943) on the expedition ship *Soya* along a constant route between Japan and Antarctica (see Fig. 4.1), during five surveys between 1956 and 1962 (Kodama, 1960; Fukushima et al., 1963).

This route passes through two intense geomagnetic anomalies around Singapore and Cape Town. Each survey started in October or November and finished the following April or May every year excepting 1957/58. The period of these latitude surveys corresponds to periods from the maximum of solar activity to near the minimum. Importantly, the obtained data are useful for investigation of threshold rigidity distribution, for determining the position of the CR equator, for estimation of coupling functions for neutron and muon components, as well as for research of long-term CR modulation depending on particle rigidities. In Fig. 4.2 voyage courses are shown along which CR measurements were carried out and in Table 4.1 gives short information on these CR latitude surveys for the period 1936–1957.

4.1.2 Corrections of Japanese CR Latitude Survey Data on the Barometric Effect and Worldwide CR Variations

According to Fukushima et al. (1963), all CR latitude survey data were corrected on barometric effect by using constant barometric coefficients for all data of



Fig. 4.1 The voyage course along which the CR measurements on the ship *Soya* were carried out (From Kodama, 1960)



Fig. 4.2 The voyage courses along which CR measurements were carried out (short information on these CR latitude surveys are given in Table 4.1) (According to Kodama, 1960)

latitude surveys: for neutron component $\beta_N = -0.77\%/mb$ and for muon component $\beta_M = -0.13\%/mb$. These barometric coefficients were determined on the basis of data above the CR latitude knee (see Section 4.1.7). Results of data correction on

Observer	Type of apparatus	Period of survey		
(1) Compton and Turner (1937)	Ionization chamber	Mar. 1936–Jan. 1937		
(2) Sekido et al., (1943)	Ionization chamber	Apr. 1937–Mar. 1939		
(3) Rose et al., (1956)	Neutron monitor	Oct. 1954		
(4) Simpson et al. (1956)	Neutron monitor	Dec. 1954		
(5) Simpson et al. (1956)	Neutron monitor	FebApr. 1955		
(6) Kodama and Miyazaki (1957)	Ionization chamber and neutron monitor	Nov. 1956–Apr. 1957		
(7) Rothwell and Quenby (1958)	Neutron monitor	FebMay 1957		
(8) Law et al., (1949)	Counter telescope	July-Aug. 1948		
(9) Storey (1958)	Neutron monitor	July-Aug. 1957		
(10) Sandstrom (1958)	Neutron monitor	Feb. 1957		

Table 4.1 Short information on CR latitude surveys in 1936–1957 (From Kodama, 1960)



Fig. 4.3 Day-to-day variation of CR intensity corrected for barometric effect throughout the first Japanese CR latitude survey. Rigid line shows the neutron component intensity (*left* scale in %) and black points are for the muon component (*right* scale in %) (According to Kodama, 1960)

barometric effect for neutron and muon component for the first Japanese CR latitude survey (November 1956–April 1957) are shown in Fig. 4.3.

Let us note that, as described in detail in Chapter 6 of the monograph Dorman (M2004), real barometric coefficients sufficiently depend on cutoff rigidity R_c (they decrease with increasing R_c) and on the level of solar activity (they decrease with increasing solar activity). The correct procedure for CR latitude survey correction on the barometric effect is described in detail in Chapter 16 of



Fig. 4.4 Approximate worldwide CR intensity variation (in %) during the first Japanese CR latitude survey (November 1956 – April 1957) for muon and neutron CR components (According to Kodama, 1960)

Dorman (M2004). Because each Japanese CR latitude survey lasted for about half a year, all latitude survey data were also corrected on worldwide CR variations on the basis of CR observations by standard neutron and muon detectors at the stations Huancayo, Mexico, Mt. Norikura, and Chicago. The data of these stations were converted to relative intensities and averaged. In Fig. 4.4 the average worldwide CR variations are shown during the first Japanese CR latitude survey (November 1956–April 1957) for muon and neutron CR components.

It was shown that, for the correction of survey data on the worldwide CR intensity variation of one stable worked station with special correction factor α which depends on the geomagnetic latitude (or on cutoff rigidity) of the position of the ship can be used. This correction factor α for NM of Mt. Norikura station was determined on the basis of data of 18 CR stations during several great Forbush decreases, and its dependence on the geomagnetic latitude is shown in Fig. 4.5.

4.1.3 Database of Japanese CR Latitude Surveys

In the first CR latitude survey (November 1956–April 1957) NM-IGY from four neutron counters and an ionization chamber were used; they were put inside the observation hut, which was specially built on the upper deck of the ship *Soya*. In the second survey (November 1958–April 1959) and in the third survey (November



1959–April 1960) only a neutron monitor was used and the observation hut was removed to the middle deck, which is lower by one stair (resulting in increasing the absorber to about $15-20 \text{ g/cm}^2$). In the fourth (November 1960–April 1961) and fifth (November 1961–April 1962) surveys, NM-IGY and an ionization chamber were used. Fukushima et al. (1963) list daily data on CR intensities for all five latitude surveys.

Table A4.1 lists (according to Fukushima et al., 1963) daily data of CR measurements during the 1956/57 expedition of the nucleonic component by neutron monitor I_N (corrected for barometric pressure I_{NP} and for the barometric effect and worldwide CR variations I_{NPW}) and the muon component by ionization chamber I_M (corrected for the barometric effect I_{MP} , given in 0.01%).

4.1.4 Geomagnetic Latitude CR Curves for Neutron and Muon Components

In Fig. 4.6 geomagnetic latitude CR curves are shown for neutron and muon components obtained during the first Japanese CR latitude survey (November 1956–April 1957).

4.1.5 CR Equator According to Measurements in Japanese Expeditions

Using the Japanese CR latitude surveys, the position of the CR equator at 107° E geographic longitude was determined: it was situated at 6° N geographical latitude (or 5° S geomagnetic latitude, see Fig. 4.7).



Fig. 4.6 Latitude CR curves for neutron and muon components obtained during the first Japanese CR latitude survey (November 1956–April 1957) (From Kodama, 1960)



4.1.6 Longitude Effect Along the CR Equator

Figure 4.8 shows the longitude effect of CR neutron intensity along the CR equator according to measurements from Japanese CR surveys at sea level in comparison with CR neutron intensity measurements on airplanes at an altitude of 18,000 ft (Rothwell, 1960).



4.1.7 The Position of Latitude Knee According to Japanese Expeditions

According to Kodama (1960), the position of the latitude knee at about 20°E geographic longitude in the southern hemisphere is much lower than the ordinary one and corresponds to 6.4 GV for cutoff rigidity calculated for the eccentric dipole model of the earth's magnetic field (see Fig. 4.9).

4.1.8 Planetary Distribution of CR Neutron Intensity

By using the above results together with the available results of the latitude surveys so far obtained by many researchers, worldwide distribution of CR neutron intensity at sea level is determined by Kodama (1960). From a comparison of the world map



Fig. 4.10 The planetary distribution of CR neutron intensity at sea level. Numerical values attached to contour lines show relative intensities in % (the minimal observed CR intensity is taken as 100%) (According to Kodama, 1960)

thus obtained (see Fig. 4.10) with various models for the earth's magnetic field, it is concluded that the geomagnetic effect of the earth's magnetic field upon CRs is mostly subjected to the geomagnetic field including higher-order terms in the earth's potential.

4.2 Swedish–USA Latitude Surveys During 1956–1959 in Connection with the International Geophysical Year

4.2.1 Latitude Surveys and the Problem of CR Cutoff Rigidities

According to Sandström et al. (1963), the CR cutoff rigidities have been the subject of much discussion since it was found that even the eccentric dipole model failed as an appropriate approximation of the terrestrial magnetic field (Rose et al., 1956; Rothwell, 1958; Katz et al., 1958). Several authors have carried out calculations accounting for the non-dipole terms of the Gaussian expansion of the field (Rothwell, 1958; Quenby and Webber, 1959; Kellogg I960; Quenby and Wenk, 1962). In the opinion of Sandström et al. (1963), the most advanced work until 1963 was that of Quenby and Wenk (1962) who, in addition, introduced corrections for



Fig. 4.11 Routes of M/S *Lommaren* from Scandinavia to South Africa and back and of M/S *Stratus* to South Africa, Australia, and back via the Suez Canal (From Pomerantz, 1972)

the penumbral effects. The problem of CR cutoff rigidities was one of the main aims of the Swedish–USA latitude surveys during 1956–1959 carried out in connection with the International Geophysical Year (Sandström et al., 1963; Pomerantz, 1972).

From October 1956 to January 1958 a neutron monitor mounted on board M/S *Lommaren* made four double voyages between Scandinavian ports and South Africa. After being transferred to M/S *Stratus*, it made two voyages (March 1958–February 1959) via South Africa to Australia and back across the Indian Ocean (Fig. 4.11). Part of the data from these expeditions have been employed for studies of the CR equator and the latitude knee (Pomerantz et al., 1958, I960a, b; Sandström et al., 1962; see review in Pomerantz, 1972). The experimental setup has been described in Pomerantz (1957). Altogether, there were 10 passages west of Africa, two passages from South Africa to Australia, and one passage each along two tracks across the Indian Ocean (Fig. 4.11).

The reductions of data were made for intervals of 1 h. The mean counting rates for 6 h were employed for the final analysis. The corresponding positions were obtained from the ship's log. Concerning the periods passed in port, a mean has been calculated for the whole stretch of such a period. To eliminate long-time intensity variations, the data have been normalized by comparison with fixed neutron monitors. All the data were normalized with respect to the neutron monitor at Uppsala. In addition, the data from the two voyages of M/S *Stratus* were normalized to the monitors at Huancayo and Uppsala by means of a linear equation.

4.2.2 CR Equator Along the Longitude 14°W

Figure 4.12 shows CR data of a latitude survey representing a typical CR equator crossing in October 1958 along the geographical longitude 14° W.

Results on all crossings of the CR equator during latitude surveys on the ships *Lommaren* and *Stratus* and determination for the CR equator location are summarized in Table 4.2.



Fig. 4.12 CR data representing a typical Equator crossing. The raw bi-hourly counting rates were corrected for variations in barometric pressure, and normalized for worldwide CR intensity variations based on the observations with neutron monitors at several fixed locations. The corrected 6-h mean counting rate is plotted as a function of geographical latitude. The curve and the corresponding point of minimum intensity were calculated by the least-squares method (From Pomerantz, 1972)

Date	Location of CR equator	Date	Location of CR equator	
November 1956	7.5° N	August 1957	6.8° N	
January 1957	8.4° N	November 1957	6.1° N	
March 1957	6.4° N	December 1957	5.5°N	
May 1957	6.3°N	April 1958	6.2° N	
July 1957	7.1° N	October 1958	6.9° N	
Mean value		$6.7^\circ\pm0.8^\circN$		

Table 4.2 Summary of CR equator determinations at longitude 14° W (based on the CR latitude surveys on the ships *Lommaren* and *Stratus*) (From Pomerantz, 1972)



Fig. 4.13 The CR intensities in different Swedish-USA latitude surveys between October 1956 and March 1959 plotted as a function of threshold rigidity computed with a geomagnetic field approximation that takes into account the contribution of higher-order terms. The data are from all six voyages (different symbols on the figure), but points in the regions where the calculated threshold rigidity values were found to be erroneous are excluded. The intensity scale represents counts per 6 h (From Pomerantz, 1972)

4.2.3 Dependencies of CR Intensity from the Cutoff Rigidity

Figure 4.13 shows dependencies of CR intensity from the cutoff (threshold) rigidity (calculated by taking into account the contribution of higher-order terms) on the basis of all Swedish–USA CR latitude surveys carried out between October 1956 and March 1959 in connection with IGY.

4.3 CR Latitude Surveys by Canadian Expeditions in 1965–1966

4.3.1 Three Canadian CR Latitude Surveys, Routes, and using Apparatus

In a series of five papers by Carmichael et al. (1969a), Carmichael and Bercovitch (1969a), Carmichael et al. (1969b, c), and Carmichael and Bercovitch (1969b),



Fig. 4.14 Routes of the three Canadian CR surveys made during 1965 and 1966 (According to Carmichael et al., 1969a)

important results of three CR latitude surveys near the minimum of solar activity 1965/66, are described. These surveys were conducted (1) in North America in the summer of 1965, (2) in Canada in December 1965, and (3) in western USA and Hawaii in the summer of 1966. The routes of three Canadian CR expeditions in 1965/66 are shown in Fig. 4.14, and in Fig. 4.15 the structures of the used shipboard neutron monitor and muon telescope are also shown.

All data were corrected on the change of air pressure (barometric effect) and worldwide CR variations according to data of several neutron monitors and muon telescopes in the world; based on these data coefficients for correction expedition data were determined. Figure 4.16 shows the time variation of CR neutron intensity according to Deep River NM and periods of all three CR latitude surveys.

Coefficients used for the correction of observed CR intensity during three Canadian expeditions on the worldwide CR intensity variation dependening on the pressure and cutoff rigidity of the point of CR measurements for shipboard neutron monitor and muon telescope are shown in Fig. 4.17.



Fig. 4.15 Structures of the neutron monitor 3-NM-64 and muon telescope 2-MT-64 used in Canadian CR expeditions 1965/66 (According to Carmichael et al., 1969a)

4.3.2 Main Results for the Expedition in Summer 1965

The main results of CR measurements during the latitude survey of summer 1965 are presented in Table A4.2. It shows data corrected on barometric and temperature effects (see description of methods in Chapters 5–8 of Dorman, M2004) as well as for worldwide secular CR variations. The route of this expedition is shown in Fig. 4.14 and, using CR neutron and muon detectors in Fig. 4.15. The time variation of CR neutron intensity according to Deep River NM and periods of all three CR latitude surveys are shown in Fig. 4.16, and in Fig. 4.17 coefficients determining the dependencies of secular variations on the pressure and cutoff rigidity of the point of CR measurements for neutron and muon components are shown.

4.3.3 CR Latitude Survey in Canada in November–December 1965

This was a small latitude survey which was carried out at sites with cutoff rigidities ≤ 2 GV. The main purpose of this survey was to investigate the high-latitude plateau in neutron and muon CR intensities, and to investigate in more details CR meteorological effects (including barometric and snow effects; for more details about these effects see in more details in Chapter 6 of monograph Dorman, M2004). The main results obtained during this expedition are shown in Table 4.3.



Fig. 4.16 Daily averages of the Deep River neutron monitor during the years 1964, 1965, and 1966 showing the periods when the overland survey was in progress (According to Carmichael and Bercovitch, 1969)

4.3.4 CR Latitude Survey in Western USA and Hawaii in Summer 1966

According to Carmichael et al. (1969b), during this expedition, a 3-NM-64 shipboard neutron telescope and 2-MT-64 shipboard muon telescope (see Fig. 4.15) were operated at 29 sites near sea level and mountains on the western seaboard of the USA and in Hawaii in May–July 1966 (see the route in Fig. 4.14). The latitude survey was started at Deep River with three runs, No. 52, 53, and 54, during which a new device for measuring the temperature of the mercury in the servo-barometer was installed and calibrated. The transport van then moved to San Francisco where



Fig. 4.17 Correction factors determining the dependencies of worldwide CR variations on the pressure at different cutoff rigidities for the shipboard neutron monitor (*top* panel, **a**) and from cutoff rigidity for the shipboard muon telescope and neutron monitor (*bottom* panel, **b**) (According to Carmichael et al., 1969a)

	e			· ·				
Run	Site	Lat. (°N)	Long. (°E)	Cut-off (GV)	Day of start (1965)	P (mm Hg)	Neutron monitor scaled rate/hour	
							Measured	Corrected
45	Deep River 4	46.10	282.50	1.02	321	752.4	1,301.4	1,323.8
46	Quonset	46.10	282.50	1.02	336	748.4	1,209.6	1,232.3
47	Kapuskasing ^a	49.42	277.50	0.71	337	733.9	1,424.8	1,447.8
48	North Bay ^a	46.70	280.58	0.95	341	730.4	1,471.7	1,500.8
49	Toronto ^a	43.68	280.63	1.33	344	743.3	1,296.4	1,318.5
50	Windsor ^a	42.27	277.03	1.56	348	743.1	1,304.2	1,315.9
51	Deep River 5	46.10	282.50	1.02	353	748.1	1.234.1	1.253.4

Table 4.3 Main results of CR measurements during the latitude survey in November–December1965 (According to Carmichael et al., 1969b).

Note: ^aMeasurements at airport.

the equipment was operated at the International Airport. Then it went to Imperial near the Mexican border, and then to the top of Mt. Palomar at about 1,870 m. On the way down Mt. Palomar, the measurements were taken at Dyche valley and then,

until May 24, at Borrego Airport which provided a fourth elevation at approximately the same cutoff rigidity 5.7 GV. On May 27, the transport van reached Mt. Hood. Near the cutoff rigidity of Mt. Hood (about 2.4 GV), the mobile equipment was operated at four different elevations including Portland Airport at sea level. On June 9, 1966, the transport van was sent by ship to Hawaii. Measurements on the island of Maui in Hawaii were started on June 26 mainly in Kula (about 1,000 m above sea level), and then on the top of Mt. Haleakala (3,600 m above sea level). During the following two weeks the mobile equipment was operated at seven different altitudes between the top of Mt. Haleakala and sea level. The main results of this expedition are listed in Table A4.3.

4.3.5 Calibrated and Extended Measurements of CR Intensity on the Aircraft at Different Altitudes and at Different Cutoff Rigidities

For calibration and extending of the above-described ground CR measurements at different altitudes and different cutoff rigidities CR measurements on the aircraft KC-135 were taken simultaneously. The first set of CR measurements at aircraft altitudes were taken when the transport van was on Mt. Palomar on May 20, 1966. The aircraft KC-135 was in the vicinity of Mt. Palomar for 2 h, during which time it circled for 46 min at an altitude of 3,080 m, and for lesser times at six other levels up to 12,700 m. The time spent at each level was enough to provide at least 40,000 counts, which corresponds to a statistical error of $\pm 0.5\%$. These measurements were taken by the airborne neutron monitor (see Fig. 4.18), constructed from lead and polyethylene by Peterson et al. (1966) which follow the Chicago pattern (Meyer and Simpson, 1955).



Fig. 4.18 The airborne neutron monitor, constructed from lead and polyethylene by Peterson et al. (1966), following the Chicago pattern (Meyer and Simpson, 1955)

4.3.6 Geographically Smoothed Geomagnetic Cutoffs Rigidities

According to Carmichael et al. (1969c), when a preliminary report on the CR latitude survey of summer 1965 was being prepared (Carmichael et al., 1965), the vertical-trajectory calculations for many of the sites were made using steps of 0.1 GV. This did not give enough accuracy for taking into account the effects of penumbra (see Section 3.11). As a result of these rough calculations, it was not possible to obtain a smooth CR latitude curve (depending on cutoff rigidity), especially in the region of Central Mexico. To solve this problem, Shea et al. (1968) developed an extensive program of trajectory calculations with steps of 0.01 GV for all sites of all three Canadian CR latitude surveys and for the world grid with steps in longitude 15° and latitude 2.5°. The geographical smoothing of calculated vertical-trajectory cutoff rigidities is shown in Fig. 4.19 for longitudes 195°, 210°, 225°, 240°, 255°, 270°, and 285° E. Using these geographical smoothing cutoff rigidities provided satisfactorily smooth CR latitude curves, even in the Central Mexico region (see Fig. 4.20).



Fig. 4.19 Geographical smoothing of calculated vertical-trajectory cutoff rigidities with 0.01 GV steps (According to Carmichael et al., 1969c on the basis of the trajectory calculations of Shea et al., 1968)



Fig. 4.20 The broken curve and open-circle points show neutron-monitor counting rates (reduced to a common depth in the atmosphere) plotted using geomagnetic rigidity cutoff values determined by the vertical-trajectory method in steps of 0.1 GV. A discontinuity or kink in the curve occurs between San Luis Potosi and Mexico City. The full points exhibit the same data plotted after modification of the vertical-trajectory cutoff rigidities (calculated in steps of 0.01 GV) by the geographical smoothing process illustrated in Fig. 4.19 (According to Carmichael et al., 1969c)

4.3.7 Final Analysis of Three Canadian CR Latitude Survey Data

The final analysis of the data of three Canadian CR latitude surveys was done by Carmichael and Bercovitch (1969) taking into account the change of barometric coefficients with altitude and cutoff rigidities of the sites of measurements as well as geographically smooth cutoff rigidities (see Section 4.3.6). The information on the barometric coefficient's changing with altitude and cutoff rigidities for the neutron monitor were discussed in detail by Dorman, (M2004, see Fig. 6.9.6 on page 347 of that book), and for the muon telescope see Fig. 4.21.

The final results for all three Canadian CR latitude surveys, for neutron monitor and muon telescope, reduced to sea level (760 mm Hg) by barometric coefficients depending on atmospheric pressure and cutoff rigidity, are shown in Table A4.4.

The final corrected latitude curve for the muon telescope is shown in Fig. 4.22.



Fig. 4.21 Barometric coefficient for the muon telescope near the minimum of solar activity in 1965 (According to Carmichael and Bercovitch, 1969)



Fig. 4.22 The normalized muon intensity as a function of geographically smoothed verticaltrajectory cutoff rigidity (According to Carmichael and Bercovitch, 1969)



Fig. 4.23 NM latitude variations at sea level near the minimum of solar activity in 1965/66. The neutron intensity (normalized to the level of latitude knee at the high latitudes) are shown as a function of geographically smoothed vertical trajectory cutoff rigidity (According to Carmichael and Bercovitch, 1969)

Figure 4.23 shows the final corrected latitude curve for the neutron monitor: neutron intensity (normalized to the level of latitude knee at high latitudes) as a function of geographically smoothed vertical-trajectory cutoff rigidity.

4.3.8 CR Latitude Effects at Different Altitudes

On the basis of CR ground measurements during the three Canadian CR expeditions and recalculations by known barometric coefficients, Carmichael and Bercovitch (1969) estimated the CR latitude effects for neutron monitor and muon telescope counting rates at different altitudes (see Table 4.4).

Geographically smoothed ver- tical-trajectory cutoff rigidity, GV	Neutron-monitor rate (% of high-latitude value)				Muon-monitor rate (% of high-latitude value)		
	1,033 g cm ⁻²	843 g cm ⁻²	680 g cm ⁻²	299 g cm ⁻²	1,033 g cm ⁻²	$\frac{843}{\mathrm{gcm^{-2}}}$	$\frac{680}{\mathrm{gcm^{-2}}}$
1	100	100	100	100			
2	99.3	99.3	99.4				
2.5	98.1	97.7	97.5				
3	96.5	95.7	94.9				
3.5	94.7	93.1	91.9				
4	92.8	90.4	88.6		100	100	100
5	88.8	85.1	82.2		99.9	99.9	99.9
6	84.7	79.8	76.3	65.0	99.6	99.1	98.7
7	80.5	74.8	70.6		99.1	97.7	96.4
8	76.5	70.0	65.4		98.5	95.9	93.7
9	72.6	65.5	60.5		97.7	94.0	90.9
10	68.9	61.3	56.1		96.9	92.1	88.1
11	65.4	57.5	52.2		95.9	90.0	85.3
12	62.1	53.9	48.4		94.7	87.8	82.4
13 14	59.3 56.7	50.8	45.2	31.6	93.2 91.4	85.4	79.4
Altitude factor	1.0	4.17	14.5	241	1.0	1.70	3.11

 Table 4.4 CR latitude effects for neutron monitor and muon telescope counting rates at different altitudes (According to Carmichael and Bercovitch, 1969)

4.3.9 Comparison of Latitude Curves for Neutron Intensity in Two Minima of Solar Activity in 1954/55 and 1965/66

Carmichael and Bercovitch (1969) compared the results obtained from the three Canadian expeditions in solar activity minimum of 1965/66, and obtained on board the ships *Labrador* and *Atka* in the minimum of 1954/55 (described in Rose et al., 1956). The routes of *Labrador* and *Atka* in 1954/55 in the northern hemisphere were almost wholly within the region of smoothed geographically vertical-trajectory cutoff rigidities (see Section 4.3.6). Figure 4.24 shows a comparison of neutron monitor latitude surveys of two minima of solar activity: in the three Canadian expeditions in the minimum of 1965/66 and in the expeditions on the ships *Labrador* in September–November 1954 and *Atka* in December 1954–April 1955.

A good agreement between the two CR latitude surveys can be seen in Fig. 4.24. It indicates (delineated by a broken curve in Fig. 4.24) that in the solar activity minimum of 1954/55, the CR latitude effect was slightly larger by about 1% than in the minimum of 1965/66. But, according to Carmichael and Bercovitch (1969), this difference must be attributed mostly to the atmospheric temperature effect: the 1954/55 data were not corrected for temperature effect, but the data of 1965 were.



Fig. 4.24 Comparison of neutron monitor latitude surveys during two minimums of solar activity: in three Canadian expeditions in the minimum of 1965/66, and on the ships *Labrador* in September–November 1954, and *Atka* in December 1954–April 1955 (According to Carmichael and Bercovitch, 1969)

4.4 NM Surveys in the Southern Ocean to Antarctica by USA, Australia, and South Africa

4.4.1 Main Results of the Latitude Survey 1994/95; Discovery of the Sea State CR Effect

Bieber et al. (1995) conducted a "shakedown cruise" from December 20, 1994 to April 17, 1995 in which the monitor was picked up in Hobart (Tasmania, Australia) and delivered to Seattle (California, USA). Figure 4.25 shows the course followed by the US Coast Guard icebreaker *Polar Star* from the time it left Hobart until it crossed the equator on the homeward voyage.

Figure 4.25 also plots the "course" of the asymptotic direction of a 17 GV particle incidence vertically on the neutron monitor. This is calculated using a new code (Bieber et al., 1992) that takes into account the time of year, time of day, and magnetosphere state (defined by the Kp index and the model of Tsyganenko, 1989). The observation data were properly corrected for the extreme influences on the neutron monitor. Besides barometric pressure, the most obvious of these is the response of the monitor to varying orientations of the ship. This effect is clearly illustrated in Fig. 4.26, which shows a plot of the shipboard neutron monitor counting rate (corrected for barometric pressure and normalized to McMurdo NM) as a function of the sea state for cutoff rigidities of less than 0.5 GV.



Fig. 4.25 Course plot (dashed line) for the US Coast Guard icebreaker *Polar Star* during part of the latitude survey south of the equator. Also shown is the calculated asymptotic direction of the mean response rigidity of about 17 GV (According to Bieber et al., 1995)



The sea-state CR effect only provides a rather crude approximation to the ship's motion (see the details about this effect in Section 16.3 of Dorman, M2004). Nevertheless, it is obvious that the effect on the data is relatively large. Response of the



Fig. 4.27 Shipboard monitor counting rate corrected for the sea-state effect and normalized to Mc-Murdo NM, as a function of calculated cutoff rigidity. Dorman functions (Dorman, 1969) indicate that results of previous latitude surveys (Moraal et al., 1989) are normalized to latitude survey data of December 20, 1994–April 17, 1995, at 10 GV, and shown by a solid line for 1976 and a dashed line for 1987 (From Bieber et al., 1995)

ship to the swells of course depends on the wind, ship speed, and the orientation of the ship's axis with respect to the wave vectors. For correction data on the seastate effect, Bieber et al. (1995) applied a fractional correction to data at all cutoff rigidities based on the fit line shown in Fig. 4.26.

The shipboard monitor counting rate as a function of calculated cutoff rigidity is shown in Fig. 4.27. For comparison the Dorman functions derived by Moraal et al. (1989) are shown from their surveys during the previous two solar minima in 1976 and 1987. These have been normalized to data of Bieber et al. (1995) at 10 GV by means of a Dorman function fit. Bieber et al. (1995) noted that values in the dataset in the critical range of 0.5 to 2 GV are comparable to the observed differences between two successive solar minima: data from the southbound pass follow the solid curve (which corresponds to 1976), while data from the northbound trend follow the dashed curve (which corresponds to 1987). According to Bieber et al. (1995), the spread in measurement data is real, and has its origin in anisotropy in the CR flux.

4.4.2 CR Spectra Deduced from Neutron Monitor Surveys

Bieber et al. (1997) noted that to be able to use neutron monitors for precise determination of particle anisotropies and spectra, it is necessary to understand both the neutron monitor energy response, or "yield function," and the spectrum of galactic CR primaries. The standard method to obtain these is a latitude survey, which is conducted with a transportable monitor. The monitor count rate N is recorded as a function of geomagnetic cutoff rigidity R_c . The negative differential of $N(R_c)$ is called the "differential response" and is simply the product of the yield function $S(R_c)$ and the galactic differential spectrum $D(R_c)$, i.e.,

$$-dN(R_{\rm c})/dR_{\rm c} = S(R_{\rm c})D(R_{\rm c}).$$

$$(4.1)$$

During the austral summer of 1995/96, a neutron monitor was operated aboard a US Coast Guard icebreaker as it traveled from San Diego, California to McMurdo, Antarctica. The survey instrument was a 3-tube NM-64 detector installed in a standard shipping container. After correction of obtained data for the barometric effect and sea-state effect (the procedure of these corrections was the same as described in Section 4.4.1), and using Eq. 4.1, the differential response of neutron monitor to the galactic CR spectrum was found. The obtained result for the minimum of solar activity in 1995/96 were compared by Bieber et al. (1997) with the differential responses also obtained with NM-64 on the basis of latitude surveys near previous minimums of solar activity (see Fig. 4.28): in 1987 (according to Moraal et al., 1989), in 1976 (Stoker et al., 1967), and in 1965 (Carmichael and Bercovitch, 1969).

As can be easily seen from Fig. 4.28, the differential response in the energy range from 1 to 8 GV is systematically higher during periods of positive solar magnetic polarity (dashed curves in Fig. 4.28) than during those of negative polarity (solid curves in Fig. 4.28), in agreement with Moraal et al. (1989).



Fig. 4.28 Neutron monitor differential responses from four latitude surveys with NM-64 detectors. Dashed and solid lines denote respectively surveys conducted during positive (1976, 1995) and negative (1965, 1987) solar magnetic polarity. Legend indicates year of survey, monitor type, and data source. Curves based on the Dorman function (Dorman, 1969), parameterization presented by Moraal et al. (1989) (According to Bieber et al., 1997)

4.4.3 Apparent Geomagnetic Cutoffs and the CR Anomaly in the Cape Town Region

According to Stoker et al. (1997), a survey of CR intensities at 30,000 feet altitude was carried out in the Southern Africa region during the minimum solar activity in September 1976 with a 1-NM-64 standard super neutron monitor aboard a South African Air Force (SAAF) C130 Hercules aircraft. The points in Fig. 4.29 are 5 min count rates of the 1-NM-64 super neutron monitor, recorded at 30,000 feet altitude during the 1976 survey. The cutoff rigidities at the time of the flights have been calculated by interpolation from the $5^{\circ} \times 15^{\circ}$ world grids of Shea and Smart (1975, 1983) for vertical cutoff rigidities, using the Bessel formula for equally spaced data points (Potgieter et al., 1980). The curve in Fig. 4.29 represents the expected latitude distribution at 30,000 feet altitude and was obtained by a transformation of the 1976 sea-level CR latitude survey to 30,000 feet altitude (Potgieter et al., 1980). This transformation was described by Stoker (1995) and Stoker and Moraal (1995). The cutoff rigidities at sea level were also interpolated from the $5^{\circ} \times 15^{\circ}$ world grids of Shea and Smart (1975, 1983) for vertically incident particles. A deviation in the 5 min count rates from the curve in Fig. 4.29 is apparent between ~4.5 and 10 GV.

Stoker et al. (1997) noted that the same deviation as shown in Fig. 4.29, was seen in all distributions of the South African aircraft CR latitude surveys between 1966 and 1976, but not in the 1965 North American/Australian CR latitude sealevel surveys of Keith et al. (1968), Stoker (1995), and Stoker and Moraal (1995).



Fig. 4.29 Count rates at 30,000 feet pressure altitude, recorded during the 1976 latitude survey and plotted against vertical cutoff rigidity. The curve was transformed from the 1976 sea-level CR latitude survey to an altitude of 30,000 ft (From Stoker et al., 1997)

The latter result implies that the vertical cutoff rigidity orders, as a parameter, the CR latitude survey data equally well in the South African region and in the North American/Australian regions. It is only in the South African region and only at aircraft altitudes that the hump appears between \sim 4.5 and 10 GV. The question now arises whether the vertical cutoff rigidity is the correct ordering parameter for CR investigations by earthbound detectors. Obliquely incident particles must inevitably contribute to the observed intensities of secondary CRs, differently at different levels in the atmosphere. The final result depends on the value of cutoff rigidity, how it is calculated, and which phenomena will be taken into account.

In fact, the cutoff rigidity at any geographic location is a function of the zenith and azimuth angles of arrival, the altitude of the detection location, and the geomagnetic conditions at the time of the measurement. Usually, it was found to be sufficient to use cutoff rigidities that were determined for vertically incident particles, using the trajectory-tracing method within International Geomagnetic Reference Fields (IGRFs) and by taking secular variations into account. Tsyganenko (1989) proposed a model that describes the external magnetic field in the earth's magnetosphere depending on the dipole tilt angle for six geomagnetic activity levels. The model includes the magnetic field ring current, the magnetic field from the magnetic tail currents, as well as the magnetopause contribution and the average magnetic effect of field-aligned currents. Stoker et al. (1997) suggest that this model combined with the IGRF, representing the geomagnetic main field for the appropriate epoch, should be used by trajectory calculations to obtain effective cutoff rigidities. To solve this important problem, Clem et al. (1997) proposed a parameter they termed the "apparent" cutoff rigidity which is intended to improve upon the vertical cutoff rigidity by including effects of obliquely incident particles (for more details, see Section 3.13).

Apparent cutoff rigidities have been calculated in Stoker et al. (1997) at locations of flights at 30,000 feet in 1976. In Fig. 4.30 the 5 min count rates of Fig. 4.29 are displayed as a function of apparent cutoff rigidity. From Fig. 4.30 it can be seen that using apparent cutoff rigidities instead of vertical cutoff rigidities, resulted in smooth distribution without the hump in Fig. 4.29. The curve was fitted to these count rates. There are small deviations from this curve, which might have resulted from the first approximation approach taken by using a simple trend line between locations at which apparent cutoff rigidities have been calculated (see, in more details, calculations of apparent cutoff rigidities in different approximations in Section 3.13).

4.4.4 Using He-3 Neutron Counters for Neutron-Component Measurements; CR Latitude Survey in 1998/99

Pyle et al. (1999) conducted a 3-NM-64 latitude survey over the period November 1998–May 1999 using, for the first time, a ³He neutron detector in place of one of the three ¹⁰BF₃ counters. The ³He detector design was developed after extensive



Fig. 4.30 Count rates of Fig. 4.29 plotted against apparent cutoff rigidities. The curve is a fit to this distribution (From Stoker et al., 1997)

simulation studies (see details on the ³He detector in Section 4.4.13 of the book Dorman, M2004). This survey, one of an annual series, covered a very wide range of cutoff rigidities, from 0 to 17.4 GV. It was found that the efficiency and energy response of the ³He detector is nearly identical to that of the ¹⁰BF₃ detector, and that these detectors can be used in a standard NM-64 monitor. Figure 4.31 shows the track of the ship *Polar Sea* for the period November 1998–April 1999, along with contours of the vertical cutoff rigidity; the monitor covered one of the widest rigidity ranges yet achieved in a shipborne survey.

As part of the program to study the ³He tubes, in December 1998, at a stopover in Honolulu (Hawaii), one of the ¹⁰BF₃ tubes was replaced in the monitor by a ³He tube. Thus, from Honolulu onward, the monitor consisted of the two ¹⁰BF₃ tubes (left and center) and one ³He tube (right). In the paper by Pyle et al. (1999) only the center ¹⁰BF₃ channel was used because of sporadic noise pickup in the left ¹⁰BF₃ channel.

Fig. 4.32 shows the overall pressure-corrected counting rate profile as a function of time (top panels) and the vertical cutoff rigidity (bottom panels), with the ³He tube plotted in black and the ¹⁰BF₃ tube in grey.

In Fig. 4.32 the calculated vertical effective geomagnetic cutoff rigidities were used from the papers Shea et al. (1965) and Cooke et al. (1991) using a trajectory code based upon the Tsyganenko (1989) magnetosphere model according to Lin et al. (1995). No corrections for changes in the modulation level have yet been made to these data; these would not be important for the counting rate ratios.

Figure 4.33 plots the variation of the ratio ${}^{3}\text{He}/{}^{10}\text{BF}_{3}$ as a function of the vertical cutoff rigidity.



Fig. 4.31 The track of the ship *Polar Sea* for the period November 1998–April 1999, along with contours of the vertical cutoff rigidity (dashed lines; numbers are vertical cutoff rigidities in GV) (From Pyle et al., 1999)



Fig. 4.32 The overall pressure-corrected counting rate profile as a function of time (*top* panels) and the vertical cutoff rigidity (*bottom* panels), with the ³He tube plotted in black and the ${}^{10}BF_3$ tube in grey (According to Pyle et al., 1999)


Fig. 4.33 Ratio of counting rates ${}^{3}\text{He}/{}^{10}\text{BF}_{3}$ as a function of the vertical cutoff rigidity (According to Pyle et al., 1999)

From Fig. 4.33 it can be seen that over a very wide range of rigidities the ratio of counting rates with counters ${}^{3}\text{He}/{}^{10}\text{BF}_{3}$ is constant to better than 1%. The predicted ratio, based on the simulations of Clem (1999), is also shown in Fig. 4.33. The measured ${}^{3}\text{He}$ NM-64 detector response is approximately 5% higher than these predictions.

4.4.5 Latitude Survey Observations of Neutron Multiplicities

Bieber et al. (2001b, 2004) augmented the electronics for the NM latitude survey so as to record the elapsed time δT between detected neutrons in each proportional tube in order to examine time correlations in the data as a function of cutoff rigidity and primary spectrum. They quantified the dependence of counting rate on NM dead time, with particular focus on the longer dead times that were once employed at the former USSR (Russian) stations. The observations of Bieber et al. (2001b, 2004) show that NM dead time has little influence on the detected depth of Forbush decreases, indicating that the CR spectral shape is little changed in the decrease. However, the use of different dead times significantly alters the response of the NM as a function of cutoff rigidity.

The earliest known measurements of the latitude-dependence of multiplicity was performed by Dyring and Sporre (1966) using a two tube IGY monitor. Subsequently, other surveys have been conducted, such as that of Aleksanyan et al. (1979). In these surveys the multiplicity of an event was determined by opening a time gate initiated by a single count and adding the additional counts that occur during the gate length. The total number of counts in each event determines the multiplicity level. Each level has an associated response function corresponding to a different median rigidity of primary particles. To gain a better understanding of this process and to provide additional checks of our simulations, Bieber et al. (2001b, 2004) augmented the electronics in the three-tube NM-64 latitude survey station to measure the elapsed time δT between counts from each proportional tube. They present an initial analysis of data acquired during the northbound segment of the 2000/01 CR latitude survey (Clem et al., 1997; Bieber et al., 2003), and compare these data to a numerical simulation. As an initial application of our results, we quantify and discuss the response differences between our stations and the former USSR stations operating prior to the mid-1980s. These stations had by design a much longer dead time than the standard NM-64 (Blokh et al., 1971). In order to extract the primary CR spectrum from the δT distribution, a separate yield function for each δT component must be developed and used in an iterative numerical de-convolution. Dorman et al., (1981) discuss such an approach. The original amplifier and discriminator circuits designed for the BP-28 neutron counters have an average dead time of 20 µs to maximize the overall count rate, while the early former USSR stations introduced a 1,200 µs dead time in an effort to move the response of the monitor to lower energy. It is very important to understand the implications of this choice when reading the literature and using data from different stations in the same analysis. The result of summing the δT distributions from different lower limits is shown in Fig. 4.34. The actual distribution is compared in each case to an exponential (dotted line) fitted at high δT values. Bieber et al. (2001b, 2004) used the simulation to generate Fig. A4.1, which shows the calculated average number of counts per incident neutron as a function of energy and dead time. These results show that the ability of an NM-64 to detect multiple evaporation neutrons from a single incident particle is nearly maximized for a dead time of $20\mu s$ and nearly minimized for $1,200\mu s$.



Fig. 4.34 The total observed counts (integral of observed δT distribution) as a function of dead time for different cutoff rigidities (According to Bieber et al., 2004)

Figure A4.2 displays the percentage reduction in counts when the circuit dead time is changed from 95 to $1200\,\mu$ s. This so-called Russian Reduction is shown as a function of time during the 2000/01 CR latitude survey along with the local effective vertical cutoff rigidity and McMurdo neutron monitor station count rates. The sun was very active during this period, but this activity had little effect on the "Russian Reduction" within observational error. These observations also imply that a Forbush decrease has very little effect on the ground spectral shape, even though it reduces the overall flux level of sea-level hadrons. However, the "Russian Reduction" shows a fairly strong dependence on cutoff rigidity. In Fig. A4.2, it increases with increasing rigidity, which implies the early Russian/former USSR stations were less sensitive to high rigidity primaries. The cutoff rigidity thus has a significant effect on both the spectral shape and the overall flux level of sea-level hadrons.

Figure 4.35 displays as a direct correlation, the percentage reduction and cutoff rigidity. The percentage reduction varies from 15.5% to 18.5% over a cutoff range from 0 to 15 GV. This dependence is quite significant, particularly since some research projects require neutron monitor accuracies better than a few percent. The rigidity dependence of the "Russian Reduction" would actually be stronger if the standard dead time of 20μ s were compared. The simulation result is also shown in this plot for comparison. The shape represents the observations fairly well; however, the simulation is roughly 15% higher than the data. This difference derives from the minor difference in the shape of the calculation and observations. These anomalies in the calculation provide interesting clues for ongoing investigation to understand the internal processes in a neutron monitor.



Fig. 4.35 Observed percentage of counts having $\delta T < 1,200 \,\mu s$ as a function of effective vertical cutoff rigidity. The curve is the result of simulation (From Bieber et al., 2004)

4.4.6 Continuing Each-Year NM Latitude Surveys: Main Results from 1994–2001

According to Bieber et al. (2001a), each year, beginning in 1994, a Bartol Research Institute, University of Tasmania, and Australian Antarctic Division collaboration conducted a neutron monitor latitude survey from the USA to McMurdo, Antarctica, and back over an approximately 6-month period. Data were taken on seven separate trips from Seattle to McMurdo and back. These are plotted in Fig. 4.36, along with selected vertical geomagnetic cutoff rigidity contours.

Counts from the three counter neutron tubes are recorded once a second, together with data from pitch-and-roll inclinometers. Pressure data and the GPS-derived latitude, longitude, and time are recorded once a minute. In Bieber et al. (2001a), the data are utilized from regions where the geomagnetic cutoff rigidities are greater than 2 GV, which eliminates many of the periods of rough seas. The $5^{\circ} \times 15^{\circ}$ of 1980.0 epoch vertical cutoff rigidity grid (Smart and Shea, 1985) was interpolated to produce an hour-by-hour set of cutoff rigidity values. During each survey, the monitor spent several weeks in the harbor at McMurdo, near the McMurdo neutron monitor. This period was used to normalize the total counting rate to the McMurdo monitor during each visit. This compensates for any instrumental changes, which may have occurred from year to year. During each survey year (approximately November–May), care was taken not to make any changes which might affect the



Fig. 4.36 Course plots for the 7 NM latitude surveys. Each is labeled at 1-week intervals from the start year of the survey (e.g., 7 for 1997/98); 1980 vertical cutoff rigidity contours are shown as dashed lines (numbers in GV) (According to Bieber et al., 2001a)

normalization. In order to remove various noise problems encountered during the trips, the counting rate data were corrected on a minute-by-minute basis, time-corrected using onboard GPS clock data, and then pressure-corrected to 760 mmHg using a pressure coefficient β (R_c) varying with cutoff rigidity R_c as follows:

$$\beta(R_{\rm c}) = -0.983515 + 0.00698286R_{\rm c}, \tag{4.2}$$

where $\beta(R_c)$ is in percent per mmHg and R_c is in GV (Clem et al., 1997). Since this series of observations was conducted during a period of frequent and often extreme changes in modulation level, the data were organized to yield the highest time resolution possible, consistent with a significant sweep over a large range of cutoff rigidities. Therefore, the 7 years of observations were divided into 24 segments, with each traverse to and from the magnetic equator (or highest R_c value) treated separately. Some segments were adjusted to avoid the inclusion of major Forbush decreases. An attempt was made to lessen the effect of other, minor modulation changes during a segment by demodulating the data using a modulation function based on the Climax NM and Haleakala NM count rates. It was assumed in Bieber et al. (2001a) that the demodulated survey count rate can be expressed as

$$S'(t) = S(t)M(R_{c},t),$$
 (4.3)

where the modulation function is according to Nagashima et al. (1989)

$$M(R_{\rm c},t) = A(t)R_{\rm c}^{-\gamma(t)}$$

$$\tag{4.4}$$

and parameters A(t) and $\gamma(t)$ are determined by observations on the Climax NM ($R_c = 3.03 \,\text{GV}$) and Haleakala NM ($R_c = 3.03 \,\text{GV}$). The examination of this procedure for several Forbush effect periods showed that the CR latitude survey data were effectively corrected to a constant level. The intervals of the 24 segments utilized are shown in Fig. 4.37, along with the McMurdo NM count rate.

For each segment in Fig. 4.37, the hourly data points were plotted against the vertical cutoff rigidity at the middle of the hour. A least-squares fit to a three-parameter Dorman function was performed for all data above 2 GV. The resulting fit was then differentiated to give the differential response. For one segment, a sample set of results is shown in Fig. 4.38.

Figure 4.39 plots spectra from a representative set of mid-Pacific segments that span the period from the approach to the last solar minimum (early 1996), through solar minimum modulation in 1997, until late April–early May, 2001. Inspection of the spectra plotted in Fig. 4.39 indicates that the region beyond 12 GV shows very little modulation change, as expected, whereas the region below 10 GV forms an envelope of 10 GV forms an envelope of curves ranging from solar minimum modulation (curves 2 and 3) to the highest modulation level (curve 9).

From Fig. 4.39 it can be seen that there is some evidence for crossing of some of the spectra (e.g., curve 8 appears to show very strong modulation at high rigidities but a marked recovery at low rigidities). This period is characterized by a very rapid recovery in low cutoff rigidity NM, and is typical of a dynamic modulation period.



Fig. 4.37 The 24 time intervals used in Bieber et al. (2001a) are numbered at the top. The McMurdo NM counting rate is also shown (From Bieber et al., 2001a)

Figure 4.40 shows spectra from all four western Pacific segments. It is apparent that curves 2 and 4 (equator to Seattle) form a separate group from curves 1 and 3 (Adelaide to equator). Bieber et al. (2001a) noted that the use of improved apparent cutoff rigidity calculations (see Section 4.4.3) will improve the agreement of these spectra among themselves, and with the larger set of mid-Pacific spectra during solar modulation cycle can be studied more exactly.

4.5 Latitude Surveys of Environmental Radiation and Soft Secondary CR Components by Italian Expeditions to Antarctica

4.5.1 Environmental Radiation and Soft Secondary CR Monitoring Along the Course of the Expeditions from Italy to Antarctica and Back

According to Galli et al. (1997a,b) and Cecchini et al. (1997a), the environmental radiation, i.e., CR and radioactivity gammas with E > 5 keV, has been continuously monitored for the first time, on a timescale of 1 min, across the Indian Ocean from Italy to the Ross Sea–Bay Terra Nova. Such measurements have been



Fig. 4.38 A sample fit of the data (for segment nine from October 14 to November 29, 1997), showing the fit to the Dorman function (*left* scale), as well as the derivative (characterized coupling function W(R), *right* scale). Least-squares fit results are shown (According to Bieber et al., 2001a)

performed during the XI (1995/96) and XII (1996/97) Italian expeditions to Antarctica on board the ship *Italica*. One of the purposes of this experiment was to measure the latitude effect of the secondary cosmic radiation with energy smaller than 5 MeV, the so-called ultra-soft CR component (Bernardini and Ferretti, 1939), and observe the X-ray spectra with E > 50keV, in order to identify the various natural and artificial airborne radionuclides along the course of *Italica* passing from the northern to the southern hemisphere. Worldwide researches on airborne natural and artificial radionuclides (Bressan et al., 1973; Larson et al., 1972; Wilkening and Clements, 1975; Wilkniss et al., 1974) with continuous (but not too long duration) monitoring of their concentration, have been made. However, no ultrasoft CR monitoring experiments with energy below 5–8 MeV have so far been carried out.



Fig. 4.39 Representative primary CR spectra from 1996 to 2001 for traverses of the central Pacific Ocean. The time intervals are shown in the upper-right corner, together with numeric keys, which are plotted on the spectra. The inset plots the McMurdo NM counting rate with the key numbers at the center of the intervals used (From Bieber et al., 2001a)

4.5.2 The Environmental Radiation and Soft Secondary CR Detectors

In order to monitor the environmental radiation during the two campaigns three identical scintillation detectors containing a cylindrical $(10 \times 20 \text{ cm}^2 \emptyset)$ NaI(Tl) monocrystal, with side and bottom shielded by 1 cm Pb and 0.2 cm Cu were designed, built, and used (see Fig. 4.41).

The working principles of the environment radiation detector have been described in detail in Cecchini et al. (1997b). Each detector $(65 \times 65 \times 130 \text{ cm}^3)$, weight about 80 kg) was provided with its own power supply as well as an acquisition and servicing computer.

During the XI Expedition (lasting from November 25, 1995 to March 23, 1996), two of the environment radiation detectors were retained on the deck of *Italica*.



Fig. 4.40 Dorman function fits (*left* scale) and derived spectra (*right* scale) for the segments west of Australia and in the western Pacific ocean. The southern hemisphere pair appears different, especially at high rigidities, from the northern. This was attributed to the use of a fixed 1980 cutoff rigidity grid (From Bieber et al., 2001a)

These detectors had a nearly total view of the sky above the horizon under about 6.6 g/cm^2 of Fe. The third detector was disembarked in Bay Terra Nova where it operated from January 14 to February 10, 1996.

4.5.3 Measured Spectra of Environmental Radiation

As an example, Figure 4.42 shows the superposed hourly spectra of environment radiation in the range 50-3,500 keV recorded at latitude 6° in the Indian Ocean.

4.5.4 Latitude Dependencies of Environmental Radiation in the 50–3,500 keV Energy Band

Figure 4.43 shows minute-by-minute count rates registered during both journeys in the 50–3,500 keV energy band. As seen from Fig. 4.43, variations of a different



Fig. 4.41 Drawing of the environment radiation and soft secondary CR detector: 1 - NaI(TI) scintillation monocrystal, 1'- quartz window, 2 - photomultiplier, 3 - multi-metal shield, 3' - 0.8 mm Al, 4 - plastic bottles of potassium hydrate, 5 - lead screen 10 mm thick, 6-1 mm Cu lining, 7-3 mm Al lining, 8 - polyurethane foam, 9-1.5 mm Al protection, 10 - rotation axis, 11 - MT input, 12 - outgoing signal (According to Galli et al., 1997a)



Fig. 4.42 Superposed-hourly consecutive spectra of the environment radiation in the range 50-3,500 keV recorded at latitude 6° in the Indian Ocean and averaged for 24 h. Vertical axis: logarithms of hourly counting rates per 10 keV channel (According to Galli et al., 1997a)



Fig. 4.43 Counts per minute in the energy range 50-3,500 keV observed during the course from Italy to Bay Terra Nova (BTN) – *left* panels, and from Bay Terra Nova to Italy – *right* panels. Results for latitude survey in 1995/96 are shown in the *upper* panels and for the survey in 1996/97 in the *bottom* panels. The abscissa shows time in hours after starting (According to Galli et al., 1997a)

nature are present. Some appear to remain rather constant from one journey to the next (e.g., 100–200 h and 850–950 h during the survey Ravenna–Bay Terra Nova in 1995/96 and in 1996/97 as well as 150–200 h during the survey Bay Terra Nova–Italy). Others show no apparent relation to features registered in the subsequent (or preceding) journey.

4.5.5 Observations of Transition Sea-to-Land Effects and "Radonic Storms" in the Environment Radiation During Latitude Surveys

One of the most conspicuous effects on environment radiation appears to be the sea-to-land transition effect (see Fig. 4.43) observed whenever the ship entered (or exited) the Italian harbors as well as Hobart (Tasmania) or Littleton (New Zealand). It shows up as a net change of more than a factor of two over distances on the order of one eighth of a mile. The spectral analysis in the radioactivity band suggests that

part of such effect could be due to a greater abundance of ²³⁸U and ²³²Th daughters on land and to a greater decrease of the former and the absence of the latter over sea.

Another registered effect is the count-rate increase when the ship *Italica* went across the Suez Canal and the Red Sea. Random events have been associated to "radonic storms": total counting-rate increases up to 100% in the 50–3,500 keV band, with a fast rise and a slower decrease, lasting 7–10h have been observed. Many of them were observed while the ship was cruising at 4–5 miles from the coast of Bay Terra Nova. Such phenomena might be related either to transport from land to sea of airborne particulate possibly associated to some meteorological perturbation or to sea-surface waves.

4.5.6 Latitude Effects of the Soft Secondary CR Components in the Energy Ranges 2.8–5.0 and 5–20 MeV

The latitude effects, measured on the secondary CR in the energy ranges 2.8–5 MeV and 5–20 MeV (i.e., ultra-soft and soft components), are shown in Fig. 4.44.



Fig. 4.44 Soft (5–20 MeV) – upper curve, and ultra-soft (2.8–5 MeV) – lower curve CR hourly pressure corrected (by using barometric coefficients -0.38 and -0.37%/mb, respectively, for soft and ultrasoft components). Data are 5-hourly smoothed versus geographic latitudes during the period December 21, 1996–March 20, 1997. The two arrows at 6°N of latitude mark the position of the CR ultra-soft component minima (According to Galli et al., 1997a)

As seen from Fig. 4.44, the observed latitude effect amounts to $\sim 19.3\%$ for CR in the range 2.8–5 MeV and $\sim 13.5\%$ for 5–20 MeV (as compared to the $\sim 7\%$ measured with a spherical ion chamber under 12 cm Pb by Compton and Turner, 1937).

4.5.7 The Main Results Obtained During Latitude Surveys of Environment Radiation and Soft Secondary CR Components

Galli et al. (1997a, b) and Cecchini et al. (1997a) concluded that the most outstanding phenomena observed during the 1995/96 and 1996/97 Italian expeditions to Antarctica on board the ship *Italica* are:

- 1. Sea-to-land transition effects for the total counting rate, with rapid increases of the order of a factor 2–3 during about 5 min within distances of 1/8 of a mile
- 2. The level of environmental radiation at Bay Terra Nova is higher than that observed at sea by almost a factor of 10
- 3. Radon storms were observed, i.e., enhancements of short duration in the level of radon daughters, that appear to be related to the presence of strong winds blowing from land (this fact seems to find confirmation in the contemporary episodes observed by two detectors separated by distances of <20 km).
- 4. By environment radiation measuring it has been shown that the detectors used can provide sufficient counting statistics for CRs to detect solar diurnal waves of 1-2%.
- 5. The transportation of radon daughters by huge atmospheric perturbations has been effective over distances of about 1,200 km.
- 6. New monitor units of similar design and with a similar NaI crystal, but heavier shielding and confirmed to a much smaller volume to be easily placed in different experimental conditions, such as underground, underwater, on marine platforms, and on high mountains, will be very useful.

4.6 Daily CR Latitude Curves Derived from the NM Worldwide Network Data

4.6.1 The Main Idea of the Method Developed by Italian Scientists

The main idea of the method supposed and developed by Italian scientists (Bachelet et al., 1972a, b, c, d; 1973) is simple and very effective: the using of daily average the CR counting rates of the NM worldwide network (about 60 neutron supermonitors of the IQSY type and neutron monitors of the IGY type see the description of detectors in Section 4.4 in Dorman, M2004), calibrated by CR latitude survey data to obtain for each day the latitude curve of the CR intensity depending on

cutoff rigidity. It is well known that the observed CR intensity on earth has a sufficient complicated anisotropy in the equatorial plane, owing to the earth's rotation. We see this anisotropy at each station as CR solar diurnal and semi-diurnal variations (in local solar time) and CR stellar diurnal and semi-diurnal variations (in the local siderial time). These variations change in time in connection with solar and magnetic activity and they are the main cause of CR intensity difference at CR stations with the same cutoff rigidities, but spaced at different longitudes. Therefore, it is not possible to use hourly CR data for obtaining latitude curves without correction on anisotropy effects. But using the daily averaged data really compensates this anisotropy and after correcting on local barometric and temperature effects (see Chapters 5–7 in Dorman, M2004) can be used for constructing CR latitude curves.

Let us note that the discussed method does not take into account the CR anisotropy perpendicular to the equatorial plane, the so-called north–south anisotropy (see the review in Dorman, 2000). This anisotropy cannot be eliminated by daily averaging hourly CR data. The method of their estimation and elimination from CR latitude survey data was developed by Belov et al. (1987, 1990, 1995), Villoresi et al. (2000), Iucci et al. (2000), and Dorman et al. (2000). Let us note that this method can be also applied for NM worldwide network data to estimate and eliminate CR north–south anisotropy from NM worldwide network data.

4.6.2 The Daily Sea-Level CR Latitude Curves Obtained from the NM Worldwide Network and CR Latitude Surveys

Bachelet et al. (1972a) presented and applied an indirect calibration procedure to the 1957–1965 data for practically the whole network of the near-sea-level NM by means of seven latitude surveys performed onboard ship or by a terrestrial vehicle. This procedure provides a set of daily latitude curves suitable for directly deriving the isotropic variations of the CR primary differential spectrum. Bachelet et al. (1972a) tried to optimize the information which can be obtained from the whole set of NM data, although it covers a limited rigidity range (2–17 GV for detailed differential variation, some tens of GV for integral variation). In fact:

- 1. In this rigidity range, the information obtained in principle by direct spectral measurements in space of CR primaries continued for many years, but in those times, it was very difficult or even impossible.
- 2. On the other hand, this range is the most suitable one for pure modulation studies on galactic CR intensity. In fact, at lower energies, time variations occasionally appear complicated by effects of direct or stored solar CRs, and, at higher energies, a much smaller modulation occurs in the presence of experimental uncertainties still far from being satisfactorily reduced.
- The NM worldwide network supplies us with a recording continuity which is not yet attained by the direct measurements in space. This continuity, however,

proves necessary in order to disentangle, among the modulation phenomena, the long-term and short-term variations by going through all the temporal details.

According to Bachelet et al. (1972a), the most obvious way of obtaining daily latitude curves of the neutron intensity from the continuous data of the network of stations is the direct intercalibration technique, used by the Rome group on the occasion of the European expedition in 1963 (Bachelet et al., 1965a, b) to derive the short-term primary spectral variations. To extend the scope of the European calibration with respect to rigidity range as well as time, the Rome group then undertook a procedure of indirect calibration, also using for calibration purposes data from mobile instruments with routes not touching the individual neutron stations. The method implies that before calculating the station calibration ratios to be used for normalization, the station data from the whole worldwide network should be corrected for pressure and for instrumental changes, and that vehicle data should be corrected for pressure and referred to a single definite primary condition (Bachelet et al., 1970).

Moreover, with accurate and normalized NM data, it is meaningful to apply the "differential method" to derive the primary spectral variations (Amaldi et al., 1963) instead of the usually used "integral method" based on the use of coupling functions (described in Dorman, M1957).

4.6.3 Using CR Latitude Survey Data for NM Calibration

In Bachelet et al. (1972a–e) data from seven surveys (see Table 4.5) were used for NM calibration. The original data from the five ship surveys (No. 1, 2, 3, 4, and 6) performed by the Uppsala group in cooperation with the Bartol Research Foundation along the routes shown in Fig. 4.45 were analyzed for internal consistency.

No.	Vehicle	Data were reduced to the av- erage primary conditions of the interval	Cutoff rigidity (GV)
1	M/S Lommaren	Jul. 1, 1957–Oct. 2, 1957	1.4-14.5
2	M/S Lommaren	Oct. 3, 1957–Jan. 13, 1958	1.3-14.5
3	M/S Stratus	Mar. 9, 1958– Sep. 4, 1958	0.9-16.9
4	M/S Stratus	Sep. 5, 1958–Feb. 9, 1959	1.0-16.7
5	Terrestrial transport, Europe	Jul. 25, 1963–Oct. 13, 1963	1.3-6.3
6	M/S Stratus	Jul. 1, 1964–Dec. 31, 1964	1.2-16.7
7	Terrestrial transport, America	May 12, 1964–May 14, 1965	0.7–13.3

Table 4.5 Short description of the seven CR latitude surveys used for checking and calibration purposes (the used detectors for surveys No. 1, 2, 3, 4, and 6 are described in Rose and Katzman 1956), for survey No. 5 – described in Bachelet et al., 1965a), for survey No. 7 – used 3-NM-IQSY (From Bachelet et al., 1972a)



Fig. 4.45 Original data from the five CR ship latitude surveys (No. 1, 2, 3, 4, and 6 of Table 4.5) corrected for pressure and for primary variations, plotted as a function of cutoff rigidity according to Shea and Smart (1966). The smooth lines are drawn through the experimental points. The ship routes are shown in the upper right corner (From Bachelet et al., 1972a)

Further data processing included accurate pressure correction by time-varying and latitude-varying coefficients and attribution of the individual daily intensities to corresponding geomagnetic rigidity thresholds, as described by Sporre and Pomerantz (1970). To optimize the correction for the primary variations occurring within the survey time, the synoptic changes shown by the whole network of the sea-level stations were used, with the whole time of each expedition as a reference interval (see Table 4.5). The data thus reduced are shown in Fig. 4.45.

The spread of the points in Fig. 4.45, about a single smooth curve is practically reduced to the order of the measurement error of the individual daily data (0.4% at high latitudes). Bachelet et al. (1972a) believe that reaching this limiting precision can be ascribed to the instrumental stability within each trip, and moreover, to the accuracy of correction for pressure and primary variations. It also gives evidence of the accuracy of the threshold rigidity calculations of Shea and Smart (1966) in this region, if we bear in mind that during each round trip, the same rigidity range was covered along four different routes (northern and southern Hemispheres, Atlantic and Indian Oceans).



Cutoff rigidity (GV)

Fig. 4.46 Terrestrial latitude surveys No. 5 and No. 7 of Table 4.5, performed in 1963 (Bachelet et al., 1965a), and in 1965 (Carmichael and Bercovitch, 1969b). The intensity in the high-latitude region is arbitrarily taken as equal to 1,000 (From Bachelet et al., 1972a)

The data from the terrestrial latitude survey performed in 1963 by the Rome group throughout Europe (survey No. 5) are based on the direct inter-rigidity cutoff calibration technique, according Bachelet et al. (1965a). The obtained latitude curve is plotted in Fig. 4.46 against cutoff rigidities according to Shea et al. (1968). Finally, the data from the terrestrial survey performed in 1965 by the Deep River group throughout America (survey No. 7), also shown in Fig. 4.46, are taken from the paper by Carmichael and Bercovitch (1969b). Details about correction for temperature and pressure effects, and for primary CR variations, can be found in the same paper and in Carmichael et al. (1969a), while the choice of rigidity cutoffs is discussed in Carmichael et al. (1969c).

4.6.4 Using Daily Sea-Level CR Latitude Curves for Studying Spectral Structure of Large Forbush Decreases

In Bachelet et al. (1972b), the daily sea-level latitude curves (obtained as it was described in Sections 4.6.1–4.6.3) were used to derive the isotropic primary spectral

variation during 14 large Forbush decreases between July 1957 and December 1965 selected as particularly suitable for accurate analysis of the pure interplanetary isotropic modulation without the contamination of spurious effects due to geomagnetic perturbations. Due to the high precision and good rigidity coverage of the data used, detailed information on the modulation function in the studied rigidity region was obtained for the first time. The CR perturbations of geomagnetic origin in Bachelet et al. (1972b) are considered as spurious when studying the pure modulation due to the solar-induced interplanetary perturbations. The effect of CR perturbations of geomagnetic origin is considered in details in Chapter 7. The effect of transient anisotropies is particularly relevant in the initial decreasing phase, is highly variable from one event to the other, and is closely connected to the particular asymmetrical geometry of the event with respect to the earth. It follows that the isotropic interplanetary modulation is best studied by avoiding the complication of the mostly anisotropic transition phase, as well as times of relevant geomagnetic storms.

The following conditions were used to choose the event for detail analysis:

- 1. Only events exceeding a 4% CR decrease at high latitudes were considered so as to keep the uncertainty in the amplitude definition fairly low.
- 2. For each event the prestorm period was taken as the longest quiet-condition interval ending one day before the beginning of the decrease (the earth well outside the perturbation volume).
- 3. The modulated intensity condition was chosen as the starting point after both the decreasing phase of the CR intensity and the recovery of the possible geomagnetic storm (to a residual depression of the horizontal component at middle latitudes $\sim 25 \,\text{nT}$) and ending when the CR residual depression is at least 80% of the full depression and, in any case, one day before the starting of a subsequent event (the earth well inside the perturbation volume). Some information on the selected events is given in Table 4.6.

Time of the event	Prestorm interval	Modulated interval	
August 1957	Aug. 27–28	Aug. 30–31	
October 1957	Oct. 9–20	Oct.23–24	
November 1957	Nov. 23–25	Nov. 27–29	
March 1958	Mar. 20–24	Mar. 26–29	
February 1959	Feb. 7–11	Feb. 15–17	
May 1959	April 25–May 9	May 12–16	
July 1959a	July 5–10	July 12–13	
July 1959b	July 5–10	July 19–20	
August 1959	Aug. 18	Aug. 20	
March–April 1960	Mar. 23–29	Apr. 3–4	
November 1960	Nov. 4–10	Nov. 17–18	
July 1961	June 24– July 11	July 15-16	
May 1963	Apr. 24–30	May 3–6	
September 1963	Sep. 4–15	Sep. 23–24	

 Table 4.6 Relevant information on the selected great CR Forbush decreases (From Bachelet et al., 1972b)



Fig. 4.47 Daily sea-level latitude curves July 5–25, 1959. The rigidity scales for the first and last curves are indicated; for other curves, the scales are shifted on 2 GV per day (According to Bachelet et al., 1972b)

The Forbush decrease modulation shows a fairly constant behavior throughout the solar cycle, with an indication, present in the individual events and emerging clearly in the average function, of a change in slope in the 5–10 GV region. In Forbush decreases, we observed the superposition of the isotropic interplanetary modulation, perturbations of geomagnetic origin, and transient anisotropies. Figure 4.47 gives an example of the daily sea-level CR latitude curves used for the analysis. These curves refer to the three-step event of July 1959 (when the largest modulation was reached through solar cycle No. 19) and offer an illustration of the quality of the revised data used and of the selection criteria for the reference times.

Figure 4.49 shows that (Bachelet et al., 1972b):

- 1. The rigidity coverage is limited only by the gap existing in the station distribution at intermediate latitudes and is fairly good in the other regions; the spread of the station points, about a single curve is fairly small.
- 2. The selected, prestorm interval (5–10 July) is completely quiet, ending one day before the July 12 event.
- 3. The intensity after the first decrease slowly recovered for 3 days, but the last day was not included in the analysis because it just preceded another event.
- 4. During the second event, a large geomagnetic storm (day 16) and a solar CR increase (day 17, for which high-latitude station data were omitted) occurred, thus preventing any analysis.
- 5. During the most depressed day of the third decrease (day 18), another large geomagnetic storm occurred, as is apparent from the anomalous shape of the curve, so that only days 19 and 20 were used for estimating the depressed level (in this case for the prestorm level it was only possible to use the same level as adopted for the first decrease.



Fig. 4.48 Average CR latitude curves N1(Rc) and N2(Rc) relative to the prestorm and modulated conditions for Forbush decreases of **a** March 1958, **b** July 1959, **c** November 1960, and **d** September 1963 (see Table 4.6)

For each event mentioned in Table 4.6, two average latitude curves were derived, corresponding to the prestorm N_1 and modulated conditions N_2 . Examples of these pairs of curves for a few events are shown in Fig. 4.48.

By the found $N_1(R)$ and $N_2(R)$ very easy to determine the prestorm $D_1(R)$ and the modulated $D_2(R)$ differential primary CR spectrums in the interval 2–17 GV:

$$D_1(R) = dN_1(R)/dR; \quad D_2(R) = dN_2(R)/dR.$$
 (4.5)



Fig. 4.49 Modulation function $M(R) = \ln (D_1(R)/D_2(R))$ for the 14 Forbush decreases listed in Table 4.6. $D_1(R)$ and $D_2(R)$ represent the isotropic primary differential spectrum in the prestorm conditions and in the modulated conditions, respectively. The solid curve is the weighted mean of all the events; it is drawn through the experimental points of each individual events after a convenient vertical translation: (1) 1957 August, (2) 1957 October, (3) 1957 November, (4) 1958 March, (5) 1959 February, (6) 1959 May, (7) 1959b July, (8) 1959a July, (9) 1959 August, (10) 1960 March, (11) 1960 November, (12) 1961 July, (13) 1963 May, (14) 1963 September

Figure 4.49 shows the primary spectral variations calculated for all 14 events of Table 4.6 in terms of modulation function

$$M(R) = \ln \left(D_1(R) / D_2(R) \right), \tag{4.6}$$

where $D_1(R)$ and $D_2(R)$ are determined by Eq. 4.5 in the rigidity interval 2–17 GV. To estimate the modulation function M(R) at higher rigidities, it was supposed that the Forbush decrease modulation function M(R) could be represented as power law above the equatorial cutoff rigidity ~17 GV; this average behavior is summarized in Fig. 4.49 by the point at R ~ 40 GV.

From Fig. 4.49 follows three important pecularities (Bachelet, 1972b):

1. The high degree of similarity of the rigidity dependence of the Forbush decrease modulation in all the events through the solar cycle (in fact, without exception, the normalized mean curve traces the points of each event within the estimated errors)

- 2. The flattening of the modulation function, visible for all the events at intermediate rigidities between 5 and 10 GV, and which clearly emerges in the mean curve
- 3. Power laws $M(R) \propto R^{-\gamma}$ with exponents $\gamma = 1.8$, 0.6, and 1.0 could be assumed to approximate this experimental curve in the subsequent rigidity intervals 2–5 GV, 5–10 GV, and \geq 10 GV.

4.6.5 Using Daily Sea-Level CR Latitude Curves for Studying the Long-Term CR Spectral Variations

In Bachelet et al. (1972c) the daily latitude curves from 1957 to 1965 are used to derive the long-term CR spectral variation, i.e., the quasi-stationary modulation associated with the solar activity cycle. As is well known, this is observed as an intensity variation in the antiphase with the solar activity and is generally interpreted in terms of the quasi-stationary propagation of galactic CR through the large-scale magnetic field and the magnetic irregularities carried outward into the interplanetary space by the solar wind. The high precision and the good rigidity resolution reached by the synoptic use of the whole worldwide network data allow us to study for the first time the detailed rigidity dependence of the solar modulation at rigidities larger than 2 GV, in any individual primary condition over the whole time considered, without any a priori hypotheses. On the other hand, the daily time resolution, never adopted before in long-term modulation studies, has proved necessary when studying the CR depression of solar cycle No. 19, which, because of its complex structure, cannot be investigated by using pure monthly averages or smoothing techniques.

In Fig. 4.50 a general picture is presented of the intensity perturbations as observed on a monthly basis in the revised intensities of the worldwide neutron monitor network from 1957 to 1965. The figure shows five time profiles corresponding to the monthly intensities averaged over five groups of NM responding to decreasing mean primary energies (from group A of the equatorial stations to group E of the high-latitude stations). Here the average of groups of 3 or 4 NM was used as representative of a typical response to the primaries. This is aimed at lowering the residual instrumental and atmospheric effects still remaining with the data after the accurate revision and inter-comparison procedure applied to all the data used (described in Sections 4.6.1–4.6.3). The experimental error of the individual monthly points is thus reduced to roughly the size of the line itself. Since the monthly averages were computed without exclusion of preselected days, the time profiles shown in Fig. 4.50 are influenced by all types of intensity perturbations. Indeed, a fine structure of occasional variations often lasting several months superposed on the general long-term variation is clearly seen. The latter includes not only the long recovery phase of solar cycle No. 19, but also fairly long intervals about the maximum and minimum solar activity.

There are two important problems related to the study of the solar-cycle variation: (1) how to separate clearly the long- and short-term modulations, as these are so



Fig. 4.50 Monthly means of NM intensity 1957–1965; each curve shows the average of the revised data for a group of stations: (A) Kampala, Lae, Ahmedabad, Kodaikanal; (B) Buenos Aires, Mt. Norikura, Mina Aguilar, Huancayo; (C) Weissenau or Munich, Hermanns, Rome; (D) Ottawa, Churchill, Mawson; (E) Climax, Sulphur Mountain, Mt. Washington. The average 1965 intensity is taken as equal to 100 (From Bachelet et al., 1972c)

intimately entangled, particularly during solar cycle No. 19; and (2) whether the pure long-term modulation, considered as a quasi-stationary phenomenon, has a rigidity dependence constant in time, or instead shows any kind of variability. To shed some light on both problems, a regression plot of the monthly intensities of group B and intensities of group E is reported in Fig. 4.51. In Fig. 4.51 data of the extreme groups of Fig. 4.50 are used (group A unfortunately does not present a complete time coverage, so it was excluded from this analysis). Different symbols are used for intensities of months with little or no Forbush decreases, with moderate Forbush decreases, and with very large Forbush decreases.

It is apparent from Fig. 4.51 that only months with little or no Forbush decreases are consistent with a single regression line (approximated by a straight line) and, hence, with a single spectral modulation. The presence of Forbush decreases of increasing amplitude causes the points to deviate steadily in a sense indicating a greater modulation at high rigidities. This is taken as a clear indication that the Forbush perturbations can be responsible for a significant deviation from a single modulation law.

For the study of the long-term spectral variations the 1957–1965 daily CR latitude curves were averaged over time intervals considered as typical of different



Fig. 4.51 Regression plot between the monthly means of the average intensity for groups B (high cutoff rigidities) and E (low cutoff rigidities) of Fig. 4.6.6. Solid circles: months with little or no Forbush decreases; solid squares: months with moderate Forbush decreases; open circles: months with very large Forbush decreases (According to Bachelet et al., 1972c)

primary conditions. According to the above discussion, all the Forbush decreases data from the beginning of the perturbation until the full recovery to the prestorm condition or to a stable intensity level were removed. Figure 4.52 shows the quiet-time latitude curves.

In Bachelet et al. (1972c), the ratios $D_{65}(R)/D_t(R)$ of the primary rigidity spectrum $D_{65}(R)$, as observed during May 1965 (the month of minimum solar modulation) and during each of the modulated-intensity time intervals a to i from Fig. 4.52 were calculated in detail between 2 and 15.5 GV based on the slopes of the latitude curves of Fig. 4.52. Moreover, global estimates of these ratios at higher rigidities were obtained by using the ratios of the intensity variations measured at the equatorial stations. The high-rigidity behavior is here summarized by a point at $R \sim 30$ GV. Figure 4.53 shows the modulation functions

$$M(R) = \ln \left(D_{65}(R) / D_t(R) \right)$$
(4.7)

derived from the curves of Fig. 4.52. The spectral variation labelled b', relative to the subinterval April 10–30, 1958 of interval b was also added, because it is the maximum quiet-time modulation observed through solar cycle No. 19.



Fig. 4.52 Average NM latitude effects (solid points and curves) relative to the following time intervals: a - 111 quiet days during July 1957–March 1958 (40% of total number of days), b - 74 quiet days during 10 April–30 June 1958 (91%), c - 232 quiet days during August 1958–April 1959 (85%), d - 115 quiet days during May–November 1959 (53%), e - 29 quiet days during February 1960 (100%), f - 31 quiet days during January 1961 (100%), g - 61 quiet days during May–June 1962 (100%), h - 31 quiet days during January 1963 (100%), i - 31 quiet days during May–June 1963 (100%), i - 31 quiet days during May–Ise to the next. The full points represent the equivalent counting rates of the individual stations calibrated by means of CR latitude surveys. The points of curves a, b, c, d are also reported, with a different symbol (open circles) after being shifted to the right by a horizontal distance equal to the abscissa displacement of subsequent curves (this makes the comparison of neighbouring curves easier) (According to Bachelet et al., 1972c)

All the spectral variations shown in Fig. 4.53 present a very similar behavior, except for cases a and d. For these, the similarity extends only up to about 10 GV, while at higher rigidities the curve is significantly flatter than for the general behavior. The solid curve drawn through the point helps in visualizing this effect. This curve was calculated as the weighted mean of the modulation functions for the homogeneous cases b, c, e, f, g and h.

The time behavior of the quiet-condition latitude curves through the recovery phase of solar cycle No. 19 is presented in Fig. 4.54.

4.6.6 Comparison of CR Latitude Curves for Long-Term and Forbush Decreases in CR Spectral Variations

In Fig. 4.55 the mean modulation functions of both phenomena (long-term and Forbush decreases) are compared after being vertically shifted so as to overlap at low



Fig. 4.53 The modulation function M(R) with respect to May 1965 for curves a to h of Fig. 4.54 (full circles and error bars), and b' is for the interval April 10–30, 1958. The solid curve is the weighted mean, conveniently translated along the vertical axis, of points of cases b, c, e, f, g, and h (According to Bachelet et al., 1972c)

rigidities. It is apparent that by assuming comparable low-rigidity modulation, the high-rigidity spectrum suffers a smaller modulation for the Forbush decreases than for the solar-cycle CR effect.

An analogous comparison of the long- and short-term CR modulation can also be made, as in Fig. 4.56, on pairs of latitude curves relative to both phenomena.

The latitude curves selected as samples of the long-term modulation are the extreme curves b' and i of Fig. 4.54. These are compared with the pair of curves for the September 1963 Forbush decrease, which occurred at the highest prestorm level of all the Forbush events analyzed in Section 4.6.4.

The data from the high-latitude mountain stations, Sulphur Mountain, Mt. Washington, and Climax, which were shown to present the maximum mod-



Fig. 4.54 Selected quiet-time latitude curves from April 1958 to May 1966. Time intervals for curves e, f, g, h, and i are described in Fig. 4.54; for curve b' – in Fig. 4.55, curves m and n correspond to February and December 1964 (From Bachelet et al., 1972c)



Fig. 4.56 Pairs of CR latitude curves relative to the solar-cycle (full lines) and Forbush decreases (dashed lines) modulation: a – May 1966; b – Forbush decrease at September 1963; c – April 1958 (According to Bachelet et al., 1972c)



ulation amplitude (group E of Fig. 4.50), have been used for a further check of the above comparison (which utilized only sea-level latitude curves). The ratio $(\Delta N/N)_E/(\Delta N/N)_D$ between the relative intensity variation observed at these mountain stations and at sea-level stations also situated above the latitude knee (group D of Fig. 4.50) turns out to be on an average of 1.31 for the CR solar-cycle variation and 1.16 for the Forbush decrease. Bachelet et al. (1972c) came to the conclusion that the CR solar-cycle and Forbush decrease modulation functions are very similar up to about 10 GV, while at higher rigidities, the CR modulation is larger for Forbush decreases than for the CR solar-cycle effect.

4.6.7 Using Daily Sea-Level CR Latitude Curves for Studying the Influence of the Primary CR Modulation on the Attenuation Coefficient of the Nucleonic Component at Different Latitudes and Altitudes

Bachelet et al. (1972d) used the daily sea-level CR latitude curves for studying the influence of the primary CR modulation on the attenuation coefficient of the



Fig. 4.57 Attenuation coefficients of the high-latitude ($R_c < 2.8 \text{ GV}$) and low-altitude (H < 750 m above sea level – s.l.) stations Oulu ($R_c = 0.81 \text{ GV}$, s.l.), Kiel, Chicago, Nera, Alert, Thule, Wilkes, and Mawson. Full circles – NM-IGY, open circles – NM-IQSY) (According to Bachelet et al., 1972d)

nucleonic component at different latitudes and altitudes. The direct investigation of the time behavior of the station attenuation coefficients is based on the largest amount of refined data so far used, i.e., the revised data of the NM-IGY during 1957–1965 and the supermonitors NM-IQSY data during 1965–1969. Bachelet et al. (1972d) based their analysis on the daily data of 41 NM-IGY monitors and 17 NM-IQSY monitors for the period 1957–1969. As an example, Figs. 4.57 and 4.58 show the time behavior of the attenuation coefficients on different CR stations.

The results of the correlation between this time behavior and the time changes of the nucleonic intensity are in agreement with the estimates based on the solar-cycle modulation of the primary spectrum described in the Section 4.6.5 (see Fig. 4.59).

4.6.8 Using Daily CR Latitude Curves for Studying the Influence of the Primary CR Modulation on the Coupling Functions of the Nucleonic Component at Sea Level and at Altitudes \sim 1,900m above Sea Level

Bachelet et al. (1973) used daily sea-level CR latitude curves for studying the influence of primary CR modulation on the coupling functions of the nucleonic component at sea level and at altitudes \sim 1,900m above sea level (for more details on coupling functions, see Chapter 3 of Dorman, M2004). The coupling functions of



Fig. 4.58 The same as in Fig. 4.59, but for stations Goose Bay, Mt. Wellington, Resolute, Leeds, Sanae, Kerguelen, Uppsala, Deep River, Inuvik, Churchill, and Ottawa. The average solar-cycle effect on attenuation coefficients is also shown in the bottom right corner (According to Bachelet et al., 1972d)

Fig. 4.59 The average change of the yearly barometric coefficient $\Delta\beta$ versus the average nucleonic intensity at high latitude ($R_c < 2.8 \text{ GV}$) and low altitude (H < 750 mabove s.l.). The intensity is normalized to the year 1965 (as 100). Full circles – cycle No. 19; open circles – cycle No. 20 (According to Bachelet et al., 1972d)



the nucleonic component of CRs at sea level and at \sim 1,900m above sea level are computed for different modulation levels in solar cycle No. 19. Bachelet et al. (1973) were the first to compute the sea-level coupling functions at four selected primary



intensity levels directly from the latitude curves. Furthermore, the detailed knowledge of the variations of the attenuation coefficient of the nucleonic component with latitude, altitude, and solar cycle (see Section 4.6.7) allows them to obtain coupling functions also at mountain altitudes by extrapolation from the sea-level latitude curves. The computed coupling functions are normalized to the intensity of NM in the polar region, i.e., they are defined as

$$W_h(R_c,t) = \frac{1}{N_h(R_c \le 1 \,\mathrm{GV},t)} \frac{\partial N_h(R_c,t)}{\partial R_c},\tag{4.8}$$

where $W_h(R_c, t) dR_c \rightarrow W_h(R, t) dR$ is the relative contribution of primary CR with rigidities *R* to *R* + d*R* to the counting rate $N_h(R_c \le 1 \text{ GV}, t)$ of a neutron monitor located at high latitude ($R_c \le 1 \text{ GV}$) at a depth *h*. Results are shown in Fig. 4.60 for sea level and in Fig. 4.61, for mountain observations of neutron component in minimum and maximum of solar activity.

4.6.9 Latitude and Altitude Dependencies of Primary Modulation Effects in Neutron Multiplicity Distribution in the NM-IQSY

The latitude and altitude dependencies of primary modulation effects in the neutron multiplicity distribution in the NM-IQSY were investigated by Iucci et al. (1971). For this they analyzed the neutron multiplicity data obtained from the stationary NM-IQSY in Rome (geomagnetic cutoff rigidity for vertical incidence $R_c = 6.3 \text{ GV}$) and Leeds ($R_c = 2.2 \text{ GV}$) during the years 1967–1969 together with those data from the European survey conducted in the summer of 1969 with a mobile 3NM-IQSY. The attenuation coefficients for different multiplicities have been estimated; the variation of these coefficients with multiplicity, latitude, and altitude are generally found



to be in agreement with other experimental and theoretical results. The latitude curves of the multiplicity intensities obtained for R_c from 0.8 to 6.3 GV are compared with those reported by Kodama and Inoue (1970). The primary modulation effect on the multiplicity distribution is studied in the case of 16 Forbush decreases; an exponent $\gamma = 0.7$ is obtained under the hypothesis of a power law for the modulation function. In Fig. 4.62 results are shown for the cutoff rigidity dependencies of multiplicity attenuation coefficients, and in Figs. 4.63 and 4.64 of intensities of different multiplicities.

In Iucci et al. (1971) the multiplicity effects during Forbush decreases were also analyzed. In order to directly compare the multiplicity dependence of the percentage amplitude $\Delta N_m/N_m$ for different events, the $\Delta N_m/N_m$ were normalized dividing



Fig. 4.63 The multiplicity latitude effects, measured in the 1969 European survey. All the latitude effects are normalized at Rome ($R_c = 6.3 \text{ GV}$) to 100; a - m = 1, b - m = 2, c - m = 3, d - m = 4, $e - m \ge 4$, $f - m \ge 6$, $g - m \ge 8$ (According to Iucci et al., 1971)

them by the corresponding percentage amplitude of the total intensity $\Delta N_{\text{tot}}/N_{\text{tot}}$. However, as no large differences outside the estimated errors seem to appear from one event to the other, for each multiplicity *m*, a weighted mean of the individual ratios $\langle (\Delta N_m/N_m)/(\Delta N_{\text{tot}}/N_{\text{tot}}) \rangle$ was computed. In Fig. 4.64 the average ratios $\langle (\Delta N_m/N_m)/(\Delta N_{\text{tot}}/N_{\text{tot}}) \rangle$ are plotted versus multiplicity *m* for the NM of Rome and Leeds. Under the assumption that the dependence of the Forbush decrease modulation function can be represented as a power law $\propto R^{-\gamma}$, the expected multiplicity dependencies of the ratios $\langle (\Delta N_m/N_m)/(\Delta N_{\text{tot}}/N_{\text{tot}}) \rangle$ have been computed for values of $\gamma = 0.5$, 1.0, 1.5 for Rome, and $\gamma = 0.5$, 0.7, 1.0 for Leeds. These curves, obtained using the coupling functions, are also shown in Fig. 4.65.

From Fig. 4.65 it can be seen that for the Rome data γ lies between 0.5 and 1.0, while for Leeds data, γ can be determined more accurately: it has a value of about 0.7 (in agreement with other estimations, see Section 4.6.4). Results obtained in Iucci et al. (1971) confirm, with a higher accuracy, the value of γ found, using multiplicity data, by Lockwood and Singh (1970) and by Kodama and Inoue (1970).



Fig. 4.64 The multiplicity latitude effects in the geomagnetic rigidity interval. The solid curves represent the average of the three latitude surveys reported by Kodama and Inoue (1970) and the dashed curves are the results of the 1969 European latitude survey: 1 - m = 1, 2 - m = 2, 3 - m = 3, 4 - m = 4 + 5, 5 - m > 6 (According to Iucci et al., 1971)



Fig. 4.65 The weighted means ratios F_m/F_{tot} of the 16 Forbush decreases recorded at Rome (*left*) and at Leeds (*right*) are plotted versus multiplicity. The multiplicity channels 4+5, ≥ 4 , and ≥ 6 are, respectively, attributed to the equivalent multiplicities 4.3, 5.3, and 8. The lines are the expected dependencies for different exponents γ in the power-law modulation function $\propto R^{-\gamma}$ for Forbush-decreases are for Rome $1 - \gamma = 0.5$, $2 - \gamma = 1.0$, and $3 - \gamma = 1.5$, and for Leeds $1 - \gamma = 0.5$, $2 - \gamma = 0.7$, and $3 - \gamma = 1.0$ (According to Iucci et al., 1971)

4.7 CR Latitude Surveys over the Territory of the Former USSR

4.7.1 CR Intensity Distribution over the Territory of the Former USSR

The CR intensity distribution over the territory of the former USSR was found for the first time by Vakulov et al. (1962). These measurements carried out on a satellite, show that the lines of equal CR intensity are rather different from those predicted by the model of the geomagnetic dipole. After this experiment, many numerical calculations with a high precision of cutoff rigidity distribution in the real geomagnetic field were carried out (see Chapter 3). In order to check the purely theoretical values of $R_{\rm c}$, it is necessary to sufficiently reduce the statistical errors of the experimental data as compared with the satellite data of Vakulov et al. (1962). This can be done by using ground-based equipment (neutron monitors and meson telescopes) with large effective areas. Using the latitude-longitude CR intensity measurements of nucleon and meson components at sea level and the ionizing component measured on balloons during three SibIZMIR (Irkutsk) expeditions in 1964 (River Yenisei), 1965 (River Yenisei, Arctic Ocean, Karelija, River Volga, Crimea, Caucasus, Caspian Sea, Middle Asia, Siberia), and 1966 (River Lena, Arctic Ocean, Chukotsk Sea, Vladivostok, East Siberia), the lines of equal CR intensity on the territory of USSR could be found (Dorman and Kovalenko, 1966; Granitsky et al., 1966, 1968; Dorman et al., 1967a, b, c, d, 1968a, b, c, 1970; a description of the expedition muon telescope was given in Dorman et al., 1969). Although the measurements were carried out in the period near minimum solar activity, the CR modulation effects were significant and, therefore, we corrected the experimental data not only for barometer and temperature effects but also for primary time variations of the intensity. In the last case, we used the data concerning the change of the primary spectrum in this period according to Dorman et al. (1967c). Figure 4.66 shows the map of lines



Fig. 4.66 Distribution of the cutoff rigidity (curves 1–4) and CR intensity (curve 5) over the territory of the former USSR. Curves 1 (According to Quenby and Wenk, 1962), 2 (According to Makino, 1963), 3 (According to Kondo and Kodama, 1965), 4 (According to Shea and Smart, 1967)

with equal CR intensity (the continuous lines were obtained by linear interpolation between the points where direct measurements were carried out).

Figure 4.66 also shows the lines of equal cutoff rigidities calculated according to Quenby and Wenk (1962), Makino (1963), Kondo and Kodama (1965), and Shea and Smart (1967). It can be seen that the best agreement between the experimental and theoretical lines in the interval 20E–100°E is obtained in the case of the model of Shea and Smart, 1967 (the numerical trajectory calculations taking into account the penumbra, see details in Chapter 3). The deviation between the experimental and calculated data east of the 100°E meridian can be due to the influence of the East-Siberian geomagnetic anomaly on the CR particle trajectories. Obviously, the six first spherical harmonics of the geomagnetic field used in Shea and Smart (1967) are not enough to take this anomaly into account.

4.7.2 Latitude Curves of Neutron Intensity and Cutoff Rigidities

When for the neutron intensity data the barometric corrections were made at points with different cutoff rigidities R_c , the dependence of barometric coefficient β (*h*) on the geomagnetic cutoff rigidity R_c was also taken into account. All the data have been corrected for the time and instrumental variations (the latter were determined by calibrating the neutron monitor with a radioactive source). The obtained corrected data on the neutron intensity were so averaged that the statistical accuracy of the measurements for each experimental point was about 0.3%. The results of the measurements of the neutron intensity as a function of the geomagnetic cutoff rigidity R_c in the dipole approximation are presented in Fig. 4.67 (the data are so normalized that the intensity at $R_c \leq 0.5$ GV was taken to be equal to 100%).

Figure 4.68 presents the same dependence as in Fig. 4.67, but R_c was calculated according to Quenby and Wenk (1962) taking into account the non-dipole terms and of the penumbra influence.

From comparing Figs. 4.67 and 4.68, it can be seen that the experimental points in Fig. 4.68 lie on a fairly smooth curve, whereas in Fig. 4.67 individual points are



Fig. 4.67 The dependence of the neutron component intensity at sea level on the geomagnetic cutoff rigidity R_c for the dipole field (According to Dorman et al., 1967c)
scattered by about (3–4%) which is by one order in excess of the statistical accuracy of the measurements. Thus, it follows from the experimental data that the geomagnetic cutoff rigidities calculated by Quenby and Wenk (1962) have a sufficiently good approximation to the true ones.

4.7.3 Coupling Functions for Neutron Component at Sea Level

From the latitude curve in Fig. 4.68, one may easily obtain the coupling functions between the primary and secondary variations of the CR using the formula

$$W_R^i(R,h_o) = -\frac{\partial N_R^i(h_o)}{N_R^i(h_o)\partial R},$$
(4.9)

i.e., the calculation of the coupling functions is reduced to the differentiation of the normalized curve of the CR latitude dependence. The coupling functions obtained in such a way are presented in Fig. 4.69 (curve 2). The same Fig. 4.69 also presents the



curve of the differential sensitivity calculated according to the data of the neutron component intensity in 1956 (curve 3) according to Webber and Quenby (1959).

It can be seen from Fig. 4.69 that curves 1 and 2 for sea level are different in the <5GV rigidity range. This difference is likely to be connected with the fact that in 1956 the solar activity level increased considerably as compared with 1954 and, hence, the intensity of the <5GV particles proved to be modulated by the 11-year cycle of the solar activity. This fact is additional confirmation of the substantial dependence of the coupling functions on the solar activity level, especially in the low-energy range.

4.7.4 Coupling Functions for the Neutron Component at Mountain Level

The coupling functions at mountain level may be easily obtained if the coupling functions at sea level and the dependence of the barometric coefficient on the geomagnetic cutoff rigidity and on altitude, i.e., $\beta(R_c, h_o)$, are known. Such a function for the neutron component has been obtained in Carmichael et al. (1965). Using determination Eq. 4.9, we shall find the relation of the coupling functions for the mountain and sea levels

$$\frac{W_{R}^{i}(R,h)}{W_{R}^{i}(R,h_{o})} = \frac{\partial N_{R}^{i}(h)N_{R}^{i}(h_{o})}{\partial N_{R}^{i}(h_{o})N_{R}^{i}(h)},$$
(4.10)

where $N_R^i(h)$ may be expressed as

$$N_{R}^{i}(h) = N_{R}^{i}(h_{o}) \exp\left(\int_{h_{o}}^{h} \beta(R,h) \,\mathrm{d}h\right).$$
(4.11)

Differentiating (4.11) with respect to *R*, we find

$$\frac{\partial N_{R}^{i}(h)}{\partial R} = \frac{\partial N_{R}^{i}(h_{o})}{\partial R} \exp\left(\int_{h_{o}}^{h} \beta(R,h) \,\mathrm{d}h\right) - N_{R}^{i}(h_{o}) \frac{\partial}{\partial R} \left(\exp\left(\int_{h_{o}}^{h} \beta(R,h) \,\mathrm{d}h\right)\right).$$
(4.12)

Substituting Eq. 4.11 and Eq. 4.12 into Eq. 4.10, we find

$$W_{R}^{i}(R,h) = W_{R}^{i}(R,h_{o}) + \int_{h_{o}}^{h} \frac{\partial \beta(R,h)}{\partial R} \mathrm{d}h.$$
(4.13)

The last term in Eq. 4.13 may be easily found by using the method of graphical differentiation and integration of the curves $\beta(R,h)$. The results of the calculation of the coupling functions for the neutron component at mountain altitude (680 mb pressure) are presented in Fig. 4.69 (curve 1).

4.7.5 Calculation of the Integral Multiplicity for the Neutron Component

The integral multiplicity $m_i(R, h_o)$, which indicates the number of secondary particles detected with an instrument from a single primary particle of various rigidities, may be calculated using the latitude dependence of the neutron component and the differential spectrum of the primary CR for the appropriate period of solar activity. Substituting Eq. 4.9 for the coupling function and for the differential spectrum into formula

$$W^{i}_{\lambda,\varphi}(R,h_{o}) = \frac{D(R)m_{i}(R,h_{o})}{N^{i}_{\lambda,\varphi}(h_{o})},$$
(4.14)

we shall obtain the formula for calculating the values of the integral multiplicities

$$m_{\text{neutr}}(R, h_o) = \frac{\left(\frac{\partial N}{\partial R}\right)_{\text{neutr}}}{\left(\frac{\partial N}{\partial R}\right)_{\text{prim}}}.$$
(4.15)

The integral multiplicity, calculated in such a way as a function of rigidity of the neutron component, is presented in Fig. 4.70. The calculations were made using the primary spectrum presented in Ginzburg and Syrovatsky (M1964).

4.7.6 The Measurements of Geomagnetic Effects by CR Telescope; the Methods for Treating the Experimental Data

The barometric coefficients for the total ionizing and hard components of CRs were determined by the method developed in Mathews (1959) which uses the data of



Fig. 4.70 The integral multiplicity for the neutron component at sea level (From Dorman et al., 1967c)

simultaneous observations at two distant points having similar conditions of CR intensity detection. It is assumed in this method that:

- 1. The points of detection have similar geomagnetic cutoff rigidities or are located above the knee of the latitude effect.
- 2. The barometric coefficients β_1 and β_2 are equal at both points.
- 3. The considered component has a negligible temperature effect or this effect is a priori excluded.

Two observation points located above the knee of the barometric effect have been selected (cutoff rigidities 4.7 GV and 2.7 GV according to calculations of Quenby and Wenk, 1962). The intensity was recorded with the same instrument at both points, the interval between the detection at each point being equal to 6 days. The correction for the temperature effect was not made because of the absence of the temperaturesounding data. However, since no appreciable seasonal variations were observed in the barometric effect from the results of the statistical analysis and since the pressures difference between these points was about 7.0 mb, the results obtained appeared to be satisfactory. The calculations were made using the formula

$$\beta = \frac{\ln I(h) - \ln I(h_o)}{h - h_o} \times 100\%, \tag{4.16}$$

where I(h) and $I(h_o)$ are the intensities observed at points with pressures h and h_o , respectively, for the vertical and for zenith angles $\theta = 33^{\circ}$ and 53° . The barometric coefficients obtained are listed in Table 4.7.

The observational data were corrected according to an exponential formula for the barometric correction by using the found barometric coefficients. The temperature corrections were determined by an integral method. The temperature coefficient densities were calculated for the primary spectrum with exponent $\gamma = 2.5$ for zenith angles $\theta = 0^{\circ}$, 33°, and 53° according to the plots from Dorman (M1957). The temperature corrections were not inserted at all the points since the temperaturesounding data for some stations were absent. In plotting the latitude-dependence curve, the points where the temperature correction was inserted were basic.

While calculating the temperature corrections the directional sensitivity of the telescope $F(\theta, \phi)$ in dependence of the zenith angle θ and azimuthal angle ϕ was taken into account according to the formula

Component		Direction	
	Vertical	$\theta = 33^{\circ}$	$\theta = 53^{\circ}$
Total ionizing	0.20 ± 0.03	0.21 ± 0.03	0.22 ± 0.05
Hard (muon)	0.15 ± 0.03	0.17 ± 0.03	0.17 ± 0.04

Table 4.7 Barometric coefficients (in %/mb) for total ionizing and hard (muon) components for vertical direction and for zenith angles $\theta = 33^{\circ}$ and 53°

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$$\alpha(h,\Delta E) = \int_{0}^{2\pi} \mathrm{d}\varphi \int_{0}^{\pi/2} F(\theta,\varphi) \alpha(h,\Delta E,\theta,\varphi) \,\mathrm{d}\theta \Big/ \int_{0}^{2\pi} \mathrm{d}\varphi \int_{0}^{\pi/2} F(\theta,\varphi) \,\mathrm{d}\theta, \quad (4.17)$$

where $\alpha(h, \Delta E, \theta, \varphi)$ are the densities of the temperature coefficients for the directional intensity (given in Dorman, M1957).

4.7.7 Cutoff Rigidities for CR Telescope: Vertical and Inclined Directions

The cutoff rigidity for the vertical direction was taken according to Quenby and Wenk (1962) calculations, taking into account the non-dipole terms of the inner geomagnetic field and of the penumbra influence. In order to obtain the cutoff rigidities for the east R_c ($E33^\circ$), R_c ($E53^\circ$) and West R_c ($W33^\circ$), R_c ($W53^\circ$) directions at zenith angles 33° and 53°, the ratios of the cutoff rigidities R_{cQW} for the vertical direction according to Quenby and Wenk (1962) to the rigidities R_{cD} , also for the vertical direction but obtained from formula for the dipole field

$$R_{\rm cD} = 59.6\cos^4\lambda \left(1 + \sqrt{1 - \sin\theta\cos\varphi\cos^3\lambda}\right)^{-2} {\rm GV}, \qquad (4.18)$$

were calculated (in Eq. 4.18 λ is the geomagnetic latitude). The transition from cutoff rigidities R_{cD} calculated according to Eq. 4.18 without taking into account the non-dipole terms of the inner geomagnetic field and the penumbra influence for $\theta = 33^{\circ}$ and 53° to the cutoff rigidities R_{cQW} when these factors were taken into account, was made by correcting the former for these ratios. The calculated cutoff rigidities are presented in Table 4.8.

	U				· · ·			
Geographical			$ heta=0^\circ$		$\theta = 33^{\circ}$		$\theta = 53^{\circ}$	
coordinat	es	$R_{\rm cD}$	$R_{\rm cQW}$	$R_{\rm cD}/R_{\rm cQW}$	East	West	East	West
N	Е							
55°10′	82°49′	3.8	2.7	1.41	3.1	2.4	3.4	2.3
$45^{\circ}11'$	33°20′	4.7	5.4	0.87	6.2	4.8	6.5	4.8
47°58′	80°24′	5.8	4.7	1.23	5.4	4.2	5.9	3.9
41°43′	44°49′	6.4	6.9	0.93	8.2	6.0	8.8	5.7
43°14′	76°56′	7.2	6.5	1.11	7.8	5.6	8.4	5.4
39°30′	63°27′	8.0	8.2	0.98	9.9	6.9	11.1	6.6
37°57′	$58^{\circ}07'$	8.2	7.7	1.06	10.6	7.3	11.7	7.1
41°25′	69°12′	8.5	7.4	1.15	9.0	6.2	17.0	5.9
36°29′	$62^{\circ}20'$	9.0	9.6	0.94	12.0	8.1	13.3	7.7

Table 4.8 Cutoff rigidities for vertical and incline directions (GV)

4.7.8 Latitude Curves for the CR Telescope

The curves of the total ionizing and hard (muon) component intensities as a function of the geomagnetic cutoff rigidity were plotted on the basis of the averaged points in Fig. 4.71 for zenith angle 33° and in Fig. 4.72 for zenith angle 53° .



Fig. 4.72 The dependence of the total (index *t*) and hard (index *h*) component intensities at sea level on the cutoff rigidities for particle arrival direction from the east at an angle of 53° to the vertical (According to Dorman et al., 1967d)

Component		Direction					
	$ heta=0^\circ$		$\theta = 53^{\circ}$				
		North, south	East	West	East		
Total ionizing Hard	$\begin{array}{c} 8.6 \pm 0.3 \\ 4.2 \pm 0.3 \end{array}$	$\begin{array}{c} 7.8 \pm 0.5 \\ 3.5 \pm 0.5 \end{array}$	8.2 ± 0.5 7.6 ± 0.5	$\begin{array}{c} 4.4 \pm 0.5 \\ 1.8 \pm 0.5 \end{array}$	4.8 ± 0.7 4.8 ± 0.7		

Table 4.9 The amplitude of the latitude effect for various components and directions of CR telescope (%)

4.7.9 Amplitudes of Latitude Effects of Various Components Measured by CR Telescope

Table 4.9 lists the amplitudes of the latitude effects of various components determined according to the curves in Figs. 4.71 and 4.72 from the geomagnetic latitude of 28° to the plateau of the latitude dependence of the corresponding components. For zenith angle $\theta = 53^{\circ}$ in the directions north, south, and west, the latitude dependence is absent within the errors. The errors presented in the plots are somewhat greater than the calculated standard errors of the mean weight (the number of hourly values of the intensity was taken as a weight) since at some points the temperature corrections were not inserted because corresponding data on temperature sounding were not available.

It can be seen from the plots in Figs. 4.71 and 4.72, and from the Table 4.9, that the latitude dependencies of the total ionizing component in the vertical and in inclined directions are greater than that of the hard component. This may be explained by the fact that the total ionizing component also includes the non-equilibrium portion of the soft component for which the primaries of lower energies influenced to a greater extent by the geomagnetic field, are responsible. As the zenith angle increases, the value of the latitude dependence for the northward and southward directions decreases, since the particles generated by more energetic primaries arrive at sea level at a greater angle to the vertical direction because of the increase of atmospheric depth. For the westward and eastward directions, apart from the increase of the atmospheric depth, the difference of the geomagnetic cutoff rigidities is also increased with increasing zenith angle. For a zenith angle of 53° in the eastward direction, the latitude dependence of the total ionizing and hard components coincide with one another within the errors. This depends on the negligible contribution of the nonequilibrium portion of the soft component to the total ionizing component for greater zenith angles.

4.7.10 The East–West CR Asymmetry

It is well known (see Chapters 1 and 2) that the geomagnetic field deviates the positively charged particles westward and therefore the CR intensity in the westward

Fig. 4.73 The east–west asymmetry: 1 - for the hard component at an angle of 33° to the vertical; 2 - for the total ionizing component at an angle of 33° to the vertical; 3 - for the hard component at an angle of 53° to the vertical (According to Dorman et al., 1967d)



direction I_W appears to be higher than that in the eastward direction I_E . This effect is denoted as the east–west asymmetry and determined by the formula

$$A_{\rm EW} = 2 \times \frac{I_{\rm W} - I_{\rm E}}{I_{\rm W} + I_{\rm E}}.\tag{4.19}$$

Figure 4.73 presents the results of the determining of the east–west asymmetry amplitude A_{EW} as a function of geomagnetic latitude λ .

Since the influence of the geomagnetic field on the CR is increased with decreasing geomagnetic latitude, the amplitude of the east–west asymmetry must increase accordingly. This is clearly seen in the plots despite the big errors in the experimental data. The east–west asymmetry decreases to zero with increasing λ for the hard component earlier than for the total ionizing component. This fact may be explained by a different influence of the geomagnetic field on the primaries forming the hard and total ionizing components. At the geomagnetic latitude, $\lambda = 28^{\circ}$, the effect of the east–west asymmetry for the total ionizing and hard components detected at angle $\theta = 33^{\circ}$ to the vertical is $(5.7 \pm 1.2)\%$ and $(4.7 \pm 1.2)\%$, respectively; for the hard component detected at angle of 53° to the vertical it is $(6.4 \pm 1.5)\%$. A small value of the east–west asymmetry at sea level (about 5–6%) as compared with the observed in stratosphere (about 50–60%) (according to Dobrotin, M1954) may be explained with a considerably smaller value of the coupling functions for a component at sea level as compared with the stratosphere. An additional flux of particles deviated westward by the geomagnetic field causes an increase in the intensity of the CR detected in the westward direction. This increase results in the fact that the latitude dependence of the intensity in the westward direction is somewhat greater than that in the eastward direction at the same cutoff rigidities.

4.7.11 Coupling Functions and Integral Multiplicities for Total Ionizing and Hard CR Components Derived from Latitude Curves

The coupling functions between primary and secondary variations of CR have been obtained from the curves in Figs. 4.71 and 4.72 using Eq. 4.9 for total ionizing and hard CR components. Results are shown in Fig. 4.74.

Besides that, the integral multiplicities presented in Fig. 4.75 have been calculated in Dorman et al. (1967d) using formulas, analogues to Eq. 4.15:

$$m_{\rm tot}(R,h_o) = \frac{\left(\frac{\partial N}{\partial R}\right)_{\rm tot}}{\left(\frac{\partial N}{\partial R}\right)_{\rm prim}}; \ m_{\rm hard}(R,h_o) = \frac{\left(\frac{\partial N}{\partial R}\right)_{\rm hard}}{\left(\frac{\partial N}{\partial R}\right)_{\rm prim}}.$$
 (4.20)

Results are shown in Fig. 4.75.



Fig. 4.74 The coupling functions between primary and secondary CR variations for total ionizing and hard CR components. The denominations are the same as in Fig. 4.71 (According to Dorman et al., 1967d)



4.7.12 Latitude Surveys and Coupling Functions for Neutron Monitor Without Lead

In Sections 4.7.1–4.7.5, we considered CR latitude survey results obtained by using standard NM with lead during expeditions over the territory of former USSR. Now the CR neutron component is, as a rule, recorded with the standard NM-IQSY neutron monitors developed in Canada on Canadian neutron counters, and then in the former USSR on the basis of Soviet neutron counters (see a description in Chapter 4 of Dorman, M2004). The search for other methods which would make it possible to have another energy sensitivity of the recording instruments has led to the understanding of the feasibility of using neutron monitor without a lead target (Sdobnov et al., 1981; Dorman et al., 1983). As was shown in Sdobnov et al. (1981), such a neutron monitor is sensitive to lower-energy particles of secondary CRs than the NM-IOSY neutron monitor, the property that is of importance to its possible usage in the spectrographic method for discriminating between the variations of atmospheric, magnetospheric, and extraterrestrial origins (see a description of this method in Chapter 3 of Dorman, M2004). The neutron monitor without a lead target used in Dorman et al. (1983), was composed of 12 neutron counters SNM-15 (length 200 cm, diameter 15 cm, developed in the USSR and usually used in NM-IQSY of Soviet CR stations) arranged in two six-counter trays mounted directly above each other and encased in polyethylene tubes with 2-cm thick walls. The measurements were taken during a cruise along the route Vladivostok - Bering Strait - Tixie in the summer of 1982 (the interval of vertical cutoff rigidities 0.5–8.1 GV). A large Forbush decrease which occured during that period made the data interpretation difficult. Therefore, the data obtained were corrected for the Forbush decrease CR variation. Three CR stations (Tixie, Magadan, Irkutsk) nearest to the expedition route and equipped with standard NM-IQSY monitors were taken to be the check stations. Standard NM-IQSY monitor data were used in the correction because a network of stations that is equipped with neutron monitors without lead does not exist. According to Rana and Yadava (1981), the Forbush decrease amplitude increases about linearly with rising geomagnetic latitude up to 58°N and remains constant



on higher geomagnetic latitudes. Bearing this in mind, Dorman et al. (1983) determined the correction as follows. The data from Magadan ($R_c = 2.16 \text{ GV}$) and Irkutsk ($R_c = 3.97 \text{ GV}$) were used to find the linear side of the geomagnetic latitude dependence of the Forbush decrease amplitude up to 58°. The constant side of the dependence was inferred from the data of high-latitude CR station Tixie ($R_c = 0.52 \text{ GV}$). According to Sdobnov et al. (1981), the amplitudes of the Forbush decreases are 1.4 times larger for neutron monitors without lead than for NM-IQSY monitors, so the correction was appropriately multiplied by a factor of 1.4.

The dots in Fig. 4.76 show the results for the 4 h values of the intensity recorded with the neutron monitor without lead as a function of the vertical cutoff rigidity.

At R_c lower than 2 GV, the mean intensity of the recorded neutrons (shown in Fig. 4.76) is

$$N_o = 3.27 \times 10^5 \text{ neutrons/4 hours.}$$
(4.21)

As can be seen from Fig. 4.66, the conventional approximation applicable to NM-IQSY data in the form (Dorman, 1969):

$$N = N_o \left(1 - \exp\left(-\alpha R_c^{-k}\right) \right) \tag{4.22}$$

proved to be insufficient in the case of a neutron monitor without lead. Approximation described by Eq. 4.22 is shown with dashed line in Fig. 4.76 for $\alpha = 8.1$, k = 1.0 obtained from the data displayed in Fig. 4.77. Its insufficiency is confirmed by the plot of the dependence of $\ln \left(\ln \left(N_o / (N_o - N) \right) \right)$ on $\ln R_c$ in Fig. 4.77 which is not rectilinear, as should have been if approximation by Eq. 4.22 had been valid.

A more accurate approximation is

$$N = N_o \left(1 - \exp\left(-\alpha \exp\left(-kR_c \right) \right) \right) \tag{4.23}$$

shown by the solid line in Fig. 4.76, because, according to Fig. 4.78 the, linear dependence



$$\ln\left(\ln\left(N_o/(N_o-N)\right)\right) = \ln\alpha - kR_c \tag{4.24}$$

holds at $\alpha = 5.00, k = 0.21$.

The coupling functions for approximation by Eq. 4.23 are determined as

$$W(R) = -\frac{b}{N_o} \frac{\partial N(R_c)}{\partial R_c} \bigg|_{R_c \to R} = \frac{bk}{1 - \exp(-\alpha)} \exp(-kR - \alpha \exp(-kR)), \quad (4.25)$$

where the normalizing factor is $b = (1 - \exp(-\alpha))^{-1}$. The coupling functions are shown in Fig. 4.79 (curve 1; the dashed lines in Figs. 4.79 and 4.80 are extrapolations, according to Eq. 4.25, to the domains where measurements were not taken).

Figure 4.79 shows for comparison the coupling function for the neutron monitor without lead (curve 2) inferred from the calculations of Sdobnov et al. (1981). The disagreement is probably associated with a different geometry of neutron monitor without lead in Sdobnov et al. (1981) where the neutron counters were encased in



Fig. 4.80 Comparison of coupling functions for neutron monitor without lead (curve 1; the dashed part – extrapolation according to Eq. 4.25 to the domains where measurements were not taken); and for NM-IQSY (curve 2; According to Aleksanyan et al., 1981)

a rectangle polyethylene box with walls of a different thickness, rather than in the standard polyethylene cylindric tubes used in Dorman et al. (1983) and usually also used for NM-IQSY.

Figure 4.80 may be used for comparison between the coupling functions of the neutron monitor without lead used in the study of Dorman et al. (1970b) and NM-IQSY inferred from the latitude measurements taken onboard r/v *Kurchatov* from November 1971 to January 1972 (Aleksanyan et al., 1981) during approximately the same level of solar activity cycle. The comparison shows that the coupling function

for the neutron monitor without lead is on average more sensitive to lower energies of primary particles than NM-IQSY. The maximum value of the coupling function for the neutron monitor without lead,

$$W_{\text{max}} = \frac{\alpha k}{1 - \exp\left(-\alpha\right)} \exp\left(-\ln\alpha - 1\right) = 7.9 \ \% / \text{GV}$$
(4.26)

at $R_{\text{max}} = 7.6 \text{ GV}$, is higher than for NM-IQSY ($W_{\text{max}} = 5.0 \%/\text{GV}$), which agrees with the results of Sdobnov et al. (1981). Therefore, the neutron monitor without lead may be used as an additional instrument with other sensitivity to primary CR variations than the usual standard NM-IQSY.

4.7.13 The Airplane CR Latitude Surveys over the Former USSR at Altitudes with Pressures of 260–400 mb

According to Dorman et al. (1970a), to investigate the CR nucleon component intensity variation at altitudes with pressures of 260–400 mb, a small neutron monitor was developed for airplane CR latitude surveys over the former USSR. These surveys were carried out in the 0–8 GV interval of cutoff rigidities in January–February 1966, i.e., near the minimum of solar activity. The coupling functions were determined from these experimental data (see Fig. 4.81).



Fig. 4.81 Coupling functions for the neutron component at altitudes with pressures of 260 and 315 mb (From Dorman et al., 1970a)



Fig. 4.83 The total ionizing component intensity for the maximum of the altitude-dependence curve as a function of the geomagnetic cutoff rigidity R_c . The value of the intensity at the point $R_c = 0.5$ GV in 1965 has been taken as 100%. Curve 1 for 1965 and curve 2 for 1964 (From Dorman and Kovalenko, 1966)

The barometer coefficient and its dependence on R_c were also estimated on the basis of measurements of CR neutron component intensity at altitudes with pressures of 260–315 mb (see Fig. 4.82).

4.7.14 The Balloon CR Latitude Surveys over the Former USSR

The CR stratospheric measurements were carried out using EK-1 radiosounds in the summer periods of 1964 and 1965 over the former USSR (Dorman and Kovalenko, 1966). Figure 4.83 presents the results of the CR intensity measurements at the maximum of the altitude dependence curve as a function of the geomagnetic cutoff rigidity (curve 1) obtained in the summer of 1965. The same Fig. 4.83 also shows the results of similar measurements of the CR intensity obtained in 1964 (curve 2).



Fig. 4.84 The primary spectrum of the CR variations from 1964 to 1965 (Dorman and Kovalenko, 1966)

From the formula

$$\frac{\Delta D(R)}{D_{1965}(R)} = \left(\frac{\partial N_{64}/\partial R_{c}}{\partial N_{65}/\partial R_{c}} - 1\right)_{R_{c} \to R}$$
(4.27)

it is easy to calculate $\Delta D(R)/D_{1965}(R)$ which is the spectrum of the primary CR variation from 1964 to 1965. The results are presented in Fig. 4.84.

It can be seen from Fig. 4.84 that the change in the primary CR intensity between 1964 and 1965 was mainly due to particles with R < 4 GV.

4.7.15 The Balloon Measurements over the Former USSR of East–West CR Asymmetry: Estimation of the Upper Limit for Antiproton/Proton Ratio

Bogomolov et al. (1968) noted, that many measurements of the CR east–west asymmetry have been carried out to determine the sign of the charge of primary particles (Vernov et al., 1949, 1952; Winckler et al., 1950; Winckler and Anderson, 1954; see also Section 4.13.2). The investigation of the composition of the primary CR is of great importance for verification of different hypotheses of the origin of CRs and of the Universe. In those times the discrepancy between theoretical and experimental values for the east–west CR asymmetry does not contradict the presence of a 10% admixture of negatively charged particles (Fradkin, 1955). The calculated value of the antiproton–proton flux ratio (the \overline{p}/p ratio) in the primary CR is about 0.1–0.3% if the nuclear reactions of the primary CR in the interstellar gas are considered to be the only source of antiprotons. The experimental value of the \overline{p}/p ratio and its accuracy depend strongly on such phenomena as albedo, return albedo, production of



Fig. 4.85 The threshold gas Cherenkov counters: a, with reflecting walls; b, with diffusing walls. 1 – steel pressure chamber; 2 – spherical mirror; 3 and 4 – cylindrical and cone-shaped mirrors; 5 – light guide; 6 – photomultiplier. All dimensions are in millimeters (From Bogomolov et al., 1968)

secondaries in the residual atmosphere or in the equipment, and inaccuracies of cutoff rigidity and penumbra calculations. To obtain a more accurate value of the \overline{p}/p ratio a detailed investigation of the spectrum of singly charged CR particles seems to be of interest in the geomagnetic threshold region in the west and east directions. In such an experiment, one does not need the primary spectrum, but long flights are necessary to accumulate meaningful data in the narrow energy region investigated.

In Bogomolov et al. (1968) the east–west asymmetry has been measured on balloons over the former USSR to obtain a more accurate value of the antiproton– proton flux ratio in the primary CR. The measurements have been carried out at middle latitudes at a depth of 10 g/cm^2 of the atmosphere and at zenith angle 60° . The telescope used for detection consisted of two scintillation counters, a lucite Cerenkov counter, and a gas Cherenkov counter (see Fig. 4.85).

The threshold of the gas Cherenkov detector has been changed from 1.7 GeV to 5-7 GeV (for protons) in flight. The earth's magnetic field was used for orientation of the device in space. The preliminary results of the experiment are given. The telescope developed for mid-latitude measurements of the primary CR spectrum of singly charged particles has the geometric factor of the device of about 10 cm^2 sr. The threshold gas Cherenkov counters used in the telescope have specular reflecting walls (Fig. 4.85, panel a) or diffusing walls (Fig. 4.85, panel b).

Cherenkov light in the counter of the first type (panel a in Fig. 4.85) is collected by spherical 2, cylindrical 3, and cone-shaped 4 mirrors and is directed through a lucite light guide 5 to a photomultiplier 6. The light collection efficiency is about 65%. The height of the gas detector is about 500 mm and the diameter is 200 mm. The diffusing counter (panel b) is coated inside with white paint (reflection coefficient 95%). The detector is viewed by a 150-mm photomultiplier 6 through a lucite window 5. The light collection efficiency is about 60% and the length of the detector is about 200 mm. The gas counters are filled with ethylene up to 60 atm. Their thresholds can be varied from 1.7 GeV to 5–7 GeV (for protons). The efficiency of registration of these counters falls with increasing energy of the detected particles. The lucite Cherenkov counter selects singly charged particles and eliminates albedo particles. The upper end of the 50 mm of lucite is painted black. Singly charged particles are counted in the main channel of the telescope if they are registered in the scintillation and lucite counters and are not registered in the gas counter. The pulses of the lucite and gas counters are analyzed by two 16-channel analyzers which are triggered by the scintillation counters. This allows the possibility of checking the electronics during operation and evaluating the energy spectrum below the geomagnetic cutoff.

The telescope has been calibrated with sea-level muons. The earth's magnetic field is used for orientation of the device in flight, the accuracy of the orientation being $\pm 3^{\circ}$. The value of the telescope zenith angle can be 30° , 45° , and 60° , and remains constant during the experiment. The device is programmed so that it is oriented in turn to west and east. An arrangement for letting the gas off the gas counter permits a change of the upper threshold of the telescope in flight according to a prescribed schedule. One can get five or six points in the singly charged particle spectrum from 1.7 to 5–7 GeV during a 5 h flight. The gas pressure in the counter and temperature is registered continuously.

In Bogomolov et al. (1968) the energy spectra of singly charged particles arriving from the east and from the west have been measured in the 1.7–5.2 GeV energy range at geomagnetic latitude $\lambda = 40^{\circ}$ N and at an altitude of 10 g/cm^2 (see Fig. 4.86) using the diffusing gas counter. The zenith angle of the telescope was 60°.



The energy thresholds of the gas counter have been calculated for given values of gas pressure and its temperature. Most of the secondary and return albedo particles have energy below 1.7 GeV. They form a background in the spectrum under investigation. The background in these measurements was 10% of the whole flux of singly charged particles. The role of the secondaries in the 2.5–5.0 GeV range is small. The obtained results in the 3.5–4.0 GeV range are in good agreement with those of Freier and Waddington (1965).

Figure 4.86 shows that the penumbra stretches at least from 1.7 to 3.5 GeV for the west and from 2.5 to 4.0 GeV for the east. The opacity of the penumbra seems to be different for west and east. From the spectra obtained, the \overline{p}/p ratio can be estimated in two different ways. The first is the comparison of the observed east-west asymmetry with that calculated for positively charged particles. For the calculation of the east-west asymmetry, one should know the spectrum and the geomagnetic cutoffs. The spectrum in this energy range has been measured by Freier and Waddington (1965) with acceptable accuracy. For the precise determination of the cutoff values in the case of a given λ and zenith angle, a detailed computation was carried out by Shea et al. (1965). Bogomolov et al. (1968) noted that there are no such calculations for the point at which the measurements were carried out. For this reason, the spectra obtained (Fig. 4.13.17) have been used only for the preliminary estimation of the cutoffs. An average value of energy in the penumbra region has been taken as an effective cutoff, i.e., 2.5 GeV for West and 3.3 GeV for east. The statistical accuracy can be improved by a comparison of the measured and calculated asymmetry in the range up to 4.1 GeV. In the considered case, the geomagnetic effects do not influence the primary spectrum above this energy. The calculated east-west asymmetry, A_{cal} , is defined as follows:

$$A_{\rm cal} = 2 \left(I_{\rm W} - I_{\rm E} \right) / \left(I_{\rm W} + I_{\rm E} \right), \tag{4.28}$$

where I_W and I_E are the fluxes of CR particles from west and east. The westeast asymmetry found in Bogomolov et al. (1968) has an amplitude of 0.71 \pm 0.15, in agreement with the expected amplitude 0.95, calculated in Freier and Waddington (1965) for only positive primary CR particles.

If one assumes that the contribution from secondary particles and re-entrant albedo is negligible in the range 1.7–4.1 GeV and the antiproton and proton spectra are identical, one can obtain 13% for the upper limit of the \overline{p}/p ratio in this energy range. The second way of estimating the \overline{p}/p ratio is to take the ratio of particle fluxes from the east and west in the 1.7–2.5 GeV energy range (see Fig. 4.86). In this case, the evaluation depends neither on the form of proton and antiproton spectra nor on the character of the geomagnetic cutoffs. Because of poor statistics and without a thorough investigation of the secondary particle spectrum, Bogomolov et al. (1968) present only an upper limit in this energy range: $\overline{p}/p \leq 0.15 \pm 0.20$.

Let us finally note that the \overline{p}/p ratio in the broad energy range was measured at the last time with a good accuracy, and it was shown that the value of this ratio also strongly depends on the sun's magnetic field polarity and modulation effects in the Heliosphere (see details in Section 1.4.6 in Dorman, M2004).

4.8 Soviet CR Survey Expeditions over the World on the Ship *Kislovodsk*

4.8.1 CR Latitude Survey During December 1967–March 1968

According to Dorman et al. (1970b), measurements of the latitude effect of the CR muon component during the period of December 1967–March 1968 were carried out on board m/s *Kislovodsk* during the voyage from Leningrad to Buenos Aires and back, using a large installation of crossed counter telescopes. The effective area of the CR detector was 2.7 m² in the vertical direction. The spatial orientation of the CR detector (owing to the special design to facilitate the free setting of the detector) remained constant during the whole period of measurements. A detailed description of the installation is given in Dorman et al. (1969).

Experimental data were corrected for the barometer effect using the exponential formula; the corrections for the temperature effect were carried out by means of the integral method (Dorman, 1954a, b, M1957; see details in Dorman, M1972, M2004). To analyze the CR latitude curves, the vertical cutoff rigidities calculated by Makino (1963) were used. For inclined directions, the cutoff rigidities were calculated according to Alpher (1950) with subsequent corrections for the real geomagnetic field including the six first terms of the expansion of the geomagnetic potential according to spherical harmonics.

The experimental data with and without temperature corrections for the general ionizing and vertical muon component (for cubical and semi-cubical geometry) are presented in Fig. 4.87. Since the statistical errors of the data were small, i.e., only 0.07% in case of 6 h data, and the temperature distribution of the atmosphere was known on the basis of measurements by balloons during the whole voyage (Dorman et al., 1968a), it was possible to estimate the influence of the air temperature on the muon component latitude effect at sea level. Figure 4.87 shows that this influence is considerable. At high latitudes, the air temperature is lower than at the equator, the atmosphere is more compressed, and muons have a shorter path from the level of generation to the level of observation and therefore the probability of their decay is smaller. Thus, the difference in the air temperature at high latitudes and at the equator leads to well-known excess of the observed latitude effect of the muon component over the real one (Dorman, 1954c). Without taking into consideration the CR temperature effect, the measured value of the muon component latitude effect turned out to be 13.5% (the difference in the muon component latitude effect for cubical and semi-cubical telescopes is negligible, it is about 0.1%). After having carried out the temperature corrections the amplitude of the latitude effect became 8.6%. Thus, the temperature contribution to the latitude effect of the muon component in the period of our measurements was 4.9%.

As can be seen from Fig. 4.87, the CR latitude curves in the southern hemisphere are not mirror reflections of those in the northern hemisphere for all CR components. The greatest discrepancy between south and north is observed in the interval of cut-off rigidities of 12.7-13.4 GV (in the northern hemisphere it is located at $2^{\circ}-13^{\circ}$ N,



Fig. 4.87 Cosmic ray latitude curves. Curves 1 and 1' – general ionizing component. Curves 2 and 2' – muon component (cubic geometry; left scale). Curves 3 and 3' – muon component (semi-cubic geometry; right scale). Full lines (1, 2 and 3) t with temperature corrections carried out according to Dorman (M1957). Dotted curves (1', 2' and 3') – without temperature corrections (According to Dorman et al., 1970b)

34°W). This discrepancy cannot be owing to differences in the measuring apparatus, to meteorological effects, or to variations in the primary spectrum of CRs since it was observed during the voyage both to and from Buenos Aires. The greatest discrepancy was observed for the east–west asymmetry (curve 4 in Fig. 4.87). From these experimental data, it can be concluded that the calculated values of the cutoff rigidities for this region do not correspond to the real values and that in the regions of geomagnetic anomalies, the description of the geomagnetic field by the six first spherical harmonics is too rough.

4.8.2 Determining the Coupling Functions

Using experimental data corrected for primary time variations, and for barometer and temperature effects, the coupling functions can be obtained according to Dorman (M1957) (see Fig. 4.88). An extrapolation was carried out to the region of rigidity R > 15 GV by the method developed in Dorman (M1957).



Fig. 4.88 Coupling functions for the muon component. Corrections were made for primary time variations, and barometer and temperature effects. Curve 1 – vertical direction. Curves 2 and 3 – inclined directions 45° and 55° to zenith, respectively. Curve 4 – vertical direction (theoretical) (According to Dorman et al., 1970b)

4.8.3 Determining the CR Equator at 28°W

In the course of the above-mentioned measurements, the CR equator was crossed in both directions at $28^{\circ}\Omega$. Figure 4.89 shows the dependence of the intensity of CR on the geographic latitude in the region of the CR equator in the case of the vertical (cubic and semi-cubic geometry) as well as of the inclined muon components (zenith angles 37° and 45° for eastern directions).

In Fig. 4.89 all corrections (for primary time variations, barometer and temperature effects) were taken into account. The latitude dependence for all CR components in Fig. 4.89 is considerable in the equator region. These data can be used to determine the position of the CR equator with high accuracy. It can be seen from Fig. 4.89 that all CR curves show minima to the north of the geographical equator, at 7° N. The accuracy in the determination of the CR equator is $\pm 0.5^{\circ}$. Figure 4.89 also shows the values of cutoff rigidities according to Makino (1963), and Kondo and Kodama (1965), which coincide in the region of the equator and display a maximum along the longitude of $28^{\circ}\Omega$ at $4^{\circ} \pm 2^{\circ}$ N. The difference between experimental and theoretical values is not significant since cutoff rigidities were calculated in steps of 5°.

Let us compare the position of the CR equator obtained in the present study with the results of other papers. According to measurements carried out on the satellites Proton - 1, Cosmos - 4 and Cosmos - 7 (Basilova et al., 1966) the CR equator along 28° 22′ W was found at 4° \pm 3° N. According to the measurements by Simpson (1956) carried out in 1948, the position of the CR equator was found along



Fig. 4.89 Position of the CR equator determined by the muon component measurements in Dorman et al. (1970b): curves l and 2 – in vertical direction for cubic and semi-cubic geometry, respectively; curves 3 and 4 – for inclined directions with zenith angles of 37° and 45° , respectively. For comparison are shown: curve 5 – values of the cutoff rigidities according to Makino (1963) and Kondo and Kodama (1965); arrow **6** – the CR equator position determined by CR satellite observations according to Basilova et al. (1966) (From Dorman et al., 1970b)

 $28^{\circ}22'W$ at $6^{\circ}\pm1^{\circ}N$. The agreement of Simpson's measurements in 1948 and measurements of Dorman et al. (1970b) in 1968, show that during two solar activity cycles the position of the CR equator remained the same within ±1 , or we can say that the secular changes of the geomagnetic field during 20 years do not have any influence on the position of the CR equator.

4.9 Soviet CR Survey Expeditions over the World on the r/v Academician Kurchatov

4.9.1 Regular CR Latitude Measurements on the r/v Academician Kurchatov

The neutron and meson CR components have been regularly measured since 1967 in the Atlantic, Pacific, and Indian Oceans onboard the research vessel (r/v)

Academician Kurchatov (Avdeev et al., 1972, 1973, 1974; Aleksanyan et al., 1979a, b, c, 1981,1982a, b, 1985). The coupling functions, integral multiplicities, and spectrum of the 11-year variation have been determined. The measurement data on the latitudinal effects of the CR neutron component was approximated by the Dorman function in the form of (Dorman, 1969)

$$N(R_{\rm c},h_o) = N_o \left(1 - \exp\left(\alpha R_{\rm c}^{-k}\right)\right), \qquad (4.29)$$

where N_o is the plateau level of the latitudinal intensity curve, and parameters α and *k* characterize a given secondary component and vary with the solar activity cycle. Parameters α and *k* in Eq. 4.29 can be found from comparison with experimental data of the latitude survey using the least-squares method. The neutron component intensity data were corrected for the barometric effect; corrections for variations of primary origin by using data on stationary CR stations were also inserted.

4.9.2 Determining of Coupling Functions on the Basis of Latitude Surveys

In the range of up to 15 GV, the coupling functions are usually determined from the latitudinal effects of the corresponding components. The expression for calculating the coupling functions is of the form, following from Eq. 4.29:

$$W_o(R,h_o) = -\left.\frac{\partial N(R_c,h_o)}{N_o \partial R_c}\right|_{R_c \to R} = \alpha k R^{-(k+1)} \exp\left(-\alpha R^{-k}\right).$$
(4.30)

According to Eq. 4.30 the coupling functions may be extrapolated in the region with rigidity R more than the maximal geomagnetic cutoff rigidity (about 15 GV). The validity of such approximation is confirmed by the following facts: first, the differential energy spectrum of the primary flux in a high-energy range is of a power form and, second, the changes in the integral multiplicity with energy also obey the power law. Throughout, the normalization condition is also satisfied. Figure 4.90 presents the coupling functions of the CR neutron component for 1967–1971, obtained in Avdeev et al. (1973).

Table 4.10 presents the locations of the coupling function peaks and the changes in the parameters α and *k* calculated from the results of measurements onboard the r/v *Academician Kurchatov*. Also presented in Table 4.10 are the calculation results on the basis of the measurements onboard an Argentine vessel *CNRC* (see CNRC, 1969).



Fig. 4.90 Coupling functions of the CR neutron component for the period of 1967–1971: 1 – 1967, 2 – 1968, 3 – 1969, 4 – 1971. From Avdeev et al. (1973)

Year of observation	Expedition	W _{max} (%/GV)	R_{\max} (GV)	Parameter α	Parameter k
1964	CNRC	6.1	3.5	7.11	0.93
1965	CNRC	5.4	3.7	7.37	0.89
1966	CNRC	5.2	3.9	7.50	0.88
1967	CNRC	4.9	4.0	7.63	0.86
1967	Kurchatov	4.6	3.6	7.45 ± 0.38	0.86 ± 0.02
1968	CNRC	4.3	4.6	7.76	0.84
1968	Kurchatov	4.4	4.3	7.57 ± 0.38	0.85 ± 0.02
1969	Kurchatov	4.1	4.5	7.79 ± 0.23	0.83 ± 0.02
1971	Kurchatov	4.2	5.0	7.73 ± 0.29	0.81 ± 0.02

Table 4.10 Locations of the coupling function peaks and the changes in the parameters α and k calculated from the results of measurements onboard the USSR r/v Academician Kurchatov and the Argentine vessel CNRC

4.9.3 The Normalizing of the Worldwide Network of CR Stations on the Basis of CR Latitude Surveys by r/v Academician Kurchatov

A possibility exists to determine the coupling functions on the basis of the neutron component observations from the worldwide network of CR stations. In fact, having the neutron component intensity data from each station and knowing the geomagnetic cutoff rigidity R_c of each station, we may "relate" the intensity data at a station

No.	CR station	Altitude (m)	Geographi Latitude	c coordinates Longitude	R_c (GV)	Normalizing factor <i>F_i</i>
1	Victoria	71	48.42°	236.68°E	1.86	4.94 ± 0.01
2	Hobart	Sea level	-42.90°	147.33°E	1.88	0.330 ± 0.001
3	Shwartmorth	80	39.90°	284.65°E	1.92	2.53 ± 0.01
4	Kiel	54	54.30°	10.10°E	2.29	4.60 ± 0.03
5	Moscow	200	55.47°	37.32°E	2.46	3.15 ± 0.02
6	Lindau	140	51.60°	10.10°E	3.00	3.65 ± 0.04
7	Halle	100	51.48°	11.97°E	3.07	0.072 ± 0.003
8	Durbes	225	50.10°	4.60°E	3.24	4.74 ± 0.01
9	Dallas	208	32.98°	263.27°E	4.35	5.19 ± 0.01
10	Hermanus	26	-34.35°	19.13°E	4.90	0.87 ± 0.01
11	Rome	60	41.90°	12.52°E	6.32	3.72 ± 0.01
12	Tbilisi	510	41.72°	44.73°E	6.67	1.59 ± 0.01
13	Alma-Ata	806	43.25°	76.93°E	6.69	2.11 ± 0.01
14	Breasben	Sea level	-25.53°	152.92°E	7.21	0.39 ± 0.01
15	Buenos-Aires	Sea level	-34.60°	301.52°E	10.63	0.32 ± 0.01
16	Kordoba	434	-34.42°	295.80°E	11.50	0.268 ± 0.003

 Table 4.11 The list of the CR stations for which normalization was made based on the r/v Academician Kurchatov latitude survey data

to the latitudinal curve and find the normalizing factors. The intensity at the station i will be determined by the expression

$$N_i(R_{ci}, h_{oi}) = F_i N_s(R_{ci}).$$
(4.31)

Here $N_s(R_{ci})$ is the intensity obtained from the corresponding curve of the latitudinal effect for the geomagnetic cutoff rigidity where the station is located, F_i is the normalizing factor of the selected station. Table 4.11 is a list of the CR stations for which normalization was made and shows the corresponding coefficients F_i for each station. The normalization was made using the curve of the latitudinal effect in the CR neutron component as measured onboard the r/v Academician Kurchatov from February 1–20, 1969. In Table 4.11, the values of R_c are according to trajectory calculations of Shea and Smart (1967).

4.9.4 Determining Integral Multiplicities

The knowledge of the coupling functions permits the integral multiplicities and the 11-year variation spectrum to be calculated. Let us remember that the integral multiplicity $m_i(R, h_o)$ characterizes the number of secondary particles of kind *i* produced in the atmosphere by a single primary particle with rigidity *R* and detected at a level with pressure h_o . From the nomination of the coupling function, it follows that

$$m_i(R, h_o) = W_{oi}(R, h_o) N_{oi}(h_o) / D(R).$$
(4.32)

The knowledge of the differential rigidity spectrum D(R) of primary particles is also necessary to calculate the integral multiplicity. The form of this spectrum was taken from the direct measurement data of Keith et al. (1968). Inclusion of the contribution from nuclei with Z > 2 may give a difference of not more than a factor of 2 (Dorman and Miroshnichenko, M1968). Figure 4.91 presents the form of the integral multiplicities for the neutron and muon CR components.



4.9.5 Determining the Primary Spectrum of Long-Term CR Variation

The coupling functions for the various measurement periods vary due changes in the primary particle spectrum. Taking account of the fact that the neutron component intensity measurement data are corrected for the meteorological effects, the integral multiplicity $m_i(R, h_o)$ does not vary with solar activity cycle and that the change in the effective geomagnetic cutoff rigidity is small (usually $\leq 0.1 \text{ GV}$), we may write the following expression for the coupling functions:

$$W_{oi}(R, h_o, t_1) = m_i(R, h_o) D(R, t_1) / N_{oi}(h_o),$$
(4.33)

$$W_{oi}(R, h_o, t_2) = m_i(R, h_o) D(R, t_2) / N_{oi}(h_o).$$
(4.34)

Then it is easy to show that

$$\frac{\Delta D(R,\Delta t)}{D(R,t_1)} = \frac{W_{oi}(R,h_o,t_1) - W_{oi}(R,h_o,t_2)}{W_{oi}(R,h_o,t_1)}.$$
(4.35)

The Eq. 4.35 makes it possible to calculate the form of the 11-year variation spectrum. Figure 4.93 presents the form of the 11-year variation spectrum obtained from the analysis of the results of the CR neutron component measurements during solar maximum.

It is characteristic that the 11-year variation amplitude increases with a decreasing of the geomagnetic cutoff rigidity, while the primary spectrum of the 11-year variation proves to decrease with increasing R. In the low-rigidity range,



Fig. 4.93 Comparison between the experimental and calculated coupling functions of the neutron component. The theoretical curves are plotted for the primary power spectrum with exponents $\gamma = 2.2, 2.6$, and 2.7 (numbers near curves). Geomagnetic cutoff rigidities are used for the latitude service experimental data according to: curve 1 (Shea and Smart, 1967), 2 (Makino, 1963), 3 (Quenby and Wenk, 1962)

 $R \leq (3-4)$ GV, the form of the 11-year variation spectrum strongly changes from year to year. During a high solar activity period, the tendency was observed for exponent γ to increase from $\gamma = 0.2-0.4$ at $R \leq (3-4)$ GV to $\gamma = 1.6-2.0$ in the region where R > 4 GV. Thus, the regular measurements of the latitudinal effects in the CR neutron component on the basis of the data of the r/v *Academician Kurchatov* make it possible to trace the character of the long-term solar cycle variation over a sufficiently long observation period relative to solar activity. The tendency is observed for the coupling functions to shift their peak toward higher rigidities and to simultaneously decrease their value with increasing solar activity.

4.9.6 Comparison of Coupling Functions Derived from CR Latitude Services with Theoretical Expected

As can be seen from Eq. 4.33, the coupling function can be easily determined if the integral multiplicity is found from consideration of the CR nuclear-meson cascade in the atmosphere. The integral multiplicity of the CR nucleon component was calculated in Avdeev et al. (1973) on the following assumptions. Each collision was assumed to be accompanied by emission of several δ -nucleons ($E \approx 150-300$ MeV). The nuclear-emulsion data (Grigorov et al., 1958; Powell et al. M1962) indicate that the energy lost for disintegration of an air atom nucleus is approximately constant and equals ≈ 400 MeV. The δ -nucleon/evaporation nucleon ratio was assumed to be constant (4.1 according to the measurements of atmospheric fluxes of slow and fast neutrons). It was also assumed that the δ -nucleons were uniformly distributed. The calculation results for the coupling functions are shown in Fig. 4.93.

In Fig. 4.93 the experimental curves obtained on the basis of the data of the r/v *Academician Kurchatov* are also presented for the sake of comparison. The theoretical curves have been plotted for the primary spectrum in the form $\propto E^{-\gamma}$ for exponents $\gamma = 2.2$, 2.6, and 2.7. The geomagnetic cutoff rigidities were determined in terms of the models: 1 – Shea and Smart (1967), 2 – Makino (1963), 3 – Quenby and Wenk (1962). It can be seen from Fig. 4.93 that the theoretical curve for $\gamma = 2.6$ and the experimental curve plotted in terms of the Shea and Smart (1967) model are in good agreement.

4.9.7 Using CR Latitude Surveys by r/v Academician Kurchatov for Checking the Cutoff Rigidities Models

In Smirnov and Ustinovich (1970), on the basis of CR latitude surveys by r/v *Academician Kurchatov*, the efficiencies of following the different cutoff rigiditymodels were investigated by comparison of the theoretical and experimental data:

- Quenby and Webber (1959) earlier considered the non-dipole character of the earth's internal field and deduced the correction which has to be applied to the dipole vertical cutoff rigidities to obtain better agreement with observed values. Quenby and Wenk (1962) improved this method by considering the shielding effect of the solid earth on particle trajectories in the penumbral region. Modifications of the previous calculations were made assuming a non-dipole field and making approximations in the penumbral region.
- 2. Makino (1963) modified the Quenby and Webber (1959) approximation by introducing penumbral corrections different from those used by Quenby and Wenk (1962) and by introducing an empirical eastward shift of the impact point. The eastward longitude correction was empirically determined to be $16^{\circ} \cos^{3} \lambda$, where λ is the geomagnetic latitude.
- 3. Shea et al. (1965) used a Fortran program to integrate the equation of motion of charged particles in any specified geomagnetic field (trajectory computed cut-off rigidity). The computer program of Dorman et al. (1966a) used in Smirnov and Ustinovich's (1970) calculation utilizes a sixth-degree simulation of the geomagnetic field for each average daily point of r/v *Academician Kurchatov* four routes. An effective cutoff rigidity was determined by summing all the allowed rigidities.

For efficiency investigation of different models of cutoff rigidities, the average daily intensity values (corrected for barometric effect) of a supermonitor and multiplicity meter obtained during four voyages of the r/v *Academician Kurchatov* have been used. The measured intensities have been plotted as a function of the vertical cutoff rigidity for three models (see Fig. 4.94) and the root mean square of the deviation of the experimental points from the best-fit curve was determined for each model.



Fig. 4.94 Corrected counting rate as a function of various models: a Quenby and Wenk (1962), b Makino (1963), c exact trajectory calculations (From Smirnov and Ustinovich, 1970)



For a quantitative estimation of dispersion, the curves obtained were approximated by third power polynomial according to the least-squares method in agreement with the counting rates. The dispersion is minimal.

4.9.8 Estimation of Coupling Functions for Total Neutron Component and Different Multiplicities

Using trajectory computed threshold rigidities, Smirnov and Ustinovich (1970) have determined the polar coupling functions of the supermonitor and multiplicity meter for the energy range of 4–17 GV. The polar coupling functions $W_{oi}(R, h_o)$ are determined by the equation

$$W_{oi}(R,h_o) = -\left.\frac{\partial N_i(R_c,h_o)}{N_{oi}\partial R_c}\right|_{R_o \to R},\tag{4.36}$$

where N_{oi} denotes the CR intensity on the plateau's part of latitude curve. Figure 4.95 shows the results of this calculation. As seen in Fig. 4.95, the coupling functions decrease with the increase of multiplicity and the maximum shifts to the side of greater energy.

4.9.9 Main Results of r/v Academician Kurchatov Expeditions in 1971/72 and 1975: Checking Cutoff Rigidities and Determining Coupling Functions

Planetary measurements of the CR neutron component were carried out on the r/v Academician Kurchatov from November 1971–January 1972 and from February–



Fig. 4.96 The routes of r/v Academician Kurchatov in 1971/72 and 1975

May 1975 in the Atlantic Ocean. A single 3-NM-IQSY section was used. The instrument was mounted on the upper deck in a room with air conditioning. The 1 h data were supplied to a recorder together with the mean-hourly values of atmospheric pressure obtained to within a ± 0.1 mb accuracy. The coordinates of the vessel were transmitted from the satellite navigation system. The map of the routes is shown in Fig. 4.96.

The cutoff rigidities for these expeditions were calculated by interpolating the vertical cutoff rigidities of Shea and Smart (1975) based on the $5^{\circ} \times 15^{\circ}$ global grid. The cutoff rigidities in given regions for 1971 were determined by interpolation of the cutoff rigidity distribution in 1965 and 1975. The corrections for barometric effects were introduced by taking into account the dependence of the barometric coefficients on cutoff rigidities. The pressure-corrected data were then corrected for the primary CR intensity variations. The corrections were inferred from the stations in the northern hemisphere. The intensity data during the periods with strong magnetic disturbances and significant Forbush-effects were excluded.



Fig. 4.97 The cutoff rigidity dependencies of the neutron component intensity obtained in 1971/72 and in 1975. The circles and crosses denote the data obtained in the southern and northern hemispheres, respectively

Figure 4.97 shows the curves of the latitude dependence of the intensity obtained for the northern and southern hemispheres. The latitude effect was approximated by the Dorman function (Dorman, 1969), described by Eq. 4.29. It can be seen from Fig. 4.97 that the experimental points obtained in 1971/72 in the North and South Atlantic diverge in the regions with cutoff rigidities of 3–5 GV. The points obtained in the southern hemisphere along the east coast line of South America are located above the points from the northern hemisphere, thereby indicating an overestimation of the calculated rigidities in that region. The temperature effect was disregarded since its inclusion would increase the divergence.

According to Shea and Smart (1975), and Tyasto et al. (1977), significant secular variation in the horizontal component of magnetic field, and hence considerable variations of cutoff rigidities, take place in the region. The trajectory calculations were made in terms of the model of the earth's magnetic field in a definite epoch (1965 in our case) and, therefore, the calculation accuracy depends on the accuracy of the magnetic field representation for the given period. The cutoff rigidities were extrapolated to other epochs in accordance with the predicted variations in the horizontal component of the magnetic field for the given period. Hence, the cutoff rigidity accuracy obtained for other epochs by means of extrapolation depends on the accuracy of the predictions. This fact probably accounts for the disagreement

Table 4.12 The positions of the maxima of the coupling functions of the neutron component and the parameters α and k in Eq. 4.30 for 1971/72 and 1975

Period	$W_{\rm max}~(\%/{ m GV})$	$R_{\rm max}~({\rm GV})$	α	k
Nov. 1971–Jan. 1972	5.04	5.39	11.03 ± 0.05	1.01 ± 0.02
FebMay 1975	5.09	4.89	9.32 ± 0.04	0.95 ± 0.02



Fig. 4.98 The coupling coefficients obtained in 1971/72 (the dashed line) and in 1975 (the solid line)

between the theoretical and experimental cutoff rigidities. Also shown in Fig. 4.97 is the latitude dependence obtained in 1975. It can be seen that all the points belong to the same curve. It will be noted that the cutoff rigidity measured in 1975 in the southern hemisphere varied only up to 5.7 GV.

The latitude curve for each cruise was used to calculate the coupling functions between the primary CR and secondary intensities of the neutron component. The coupling functions were calculated according to Eq. 4.30. Table 4.12 presents the positions of the maxima of the coupling functions of the neutron component and the parameters α and k in Eq. 4.30. The values of the coupling functions obtained in 1971/72 are presented for the northern hemisphere data.

Figure 4.98 shows the coupling functions. The values obtained in the quiet period 1975 near minimum solar activity are most accurate. The measurements of 1971/72 were carried out during the disturbed period.

4.9.10 Main Results of the r/v Academician Kurchatov Expedition in 1982: Determining Coupling Functions for Without-Lead NM and for NM-IQSY Total Intensity and Different Multiplicities; Distribution Function of Multiplicities Depending on Cutoff Rigidity

According to Aleksanyan et al. (1985), the latitudinal behavior of total neutron intensities and multiplicities was registered by the standard 2NM-IQSY and by the lead-free neutron monitor 3SND (three counters Slow-Neutron Detector) during the expedition in 1985 onboard r/v *Academician Kurchatov* in the Atlantic Ocean. Correction due to atmospheric pressure variation was made by barometric coefficients depending on cutoff rigidity. The correction due to variations of extraterrestrial origin was introduced according to the Kiel NM-IQSY station. The geomagnetic cutoff rigidities were determined according to Shea and Smart (1967). The results of latitudinal measurements are shown in Figs. 4.99 and 4.100 by black points.



Fig. 4.99 CR latitude dependencies for standard 2NM-IQSY and lead-free neutron monitor 3SND. Black points – the observations, curves – approximation by the Dorman function according to Eq. 4.29 (From Aleksanyan et al., 1985)




The approximation of the dependence of the recorded intensity $N(R_c, h_o)$ on the geomagnetic cutoff rigidity R_c is usually described by the Dorman function according to Eq. 4.29, and determined by three constants: intensity in polar region N_o , and two parameters α and k. Usually, the value N_o , is directly determined from experimental data, and in this case the remaining two parameters α and k can be easily determined from the regression equation (following from Eq. 4.29):

$$\ln\left(\ln\left(N_o/(N_o-N(R_c,h_o))\right)\right) = \ln\alpha - k\ln R_c, \tag{4.37}$$

where R_c is in GV. However, not for all expeditions was it possible to directly measure value N_o (because a statistical accuracy of measurements rapidly decreases as multiplicity increases, and because in many cases the data of measurements in polar zones are absent as in the case of expedition in 1982). From the other side, it appears impossible to simultaneously determine three parameters N_o , α , and k from Eq. 4.29 (consider it as a regression equation) by the method of least-squares because of divergency of the iteration process.

The successive approximation method based on Demidovich et al. (M1962) was proposed in Aleksanyan et al. (1985) for finding all three parameters of the approximation described by Eq. 4.29. The expansion of Eq. 4.29. in a Taylor series with an accuracy to first-order terms at the point of the initial approximation of parameters has the form

$$N(R_{\rm c},h_o) = \left[N_o\left(1 - \exp\left(-\alpha R_{\rm c}^{-k}\right)\right)\right]_0 + \left[1 - \exp\left(-\alpha R_{\rm c}^{-k}\right)\right]_0 \Delta N_o$$
$$+ \left[N_o R_{\rm c}^{-k} \exp\left(-\alpha R_{\rm c}^{-k}\right)\right]_0 \Delta \alpha + \left[N_o \alpha R_{\rm c}^{-k} \ln\left(R_{\rm c}\right) \exp\left(-\alpha R_{\rm c}^{-k}\right)\right]_0 \Delta k,$$
(4.38)

where the expressions in quadrantal brackets are taken at the point of the initial approximation $N_o = N_o^{(0)}$, $\alpha = \alpha^{(0)}$, $k = k^{(0)}$. Then one minimizes the sum of the squares of the differences of the calculated values of $N(R_c, h_o)$ according to Eq. 4.38 and experimental values of $N(R_c, h_o)$:

$$S = \Sigma \left(q \Delta N_o + N_o r \Delta \alpha - N_o \alpha r \ln r \Delta k - N_o q - N \left(R_c, h_o \right) \right) = \min, \quad (4.39)$$

where

$$q = 1 - \exp\left(\alpha R_{\rm c}^{-k}\right); \quad r = R_{\rm c}^{-k} \exp\left(-\alpha R_{\rm c}^{-k}\right). \tag{4.40}$$

The condition of the minimum described by Eq. 4.39 leads to

$$\partial S/\partial N_o = 0, \ \partial S/\partial \alpha = 0, \ \partial S/\partial k = 0.$$
 (4.41)

It gives the system of equations

$$\begin{cases} \Delta N_o \sum q^2 + N_o \Delta \alpha \sum qr - N_o \alpha \Delta k \sum qr \ln R_c = \sum q \left(N - N_o q \right) \\ \Delta N_o \sum qr N_o + N_o \Delta \alpha \sum r^2 - N_o \alpha \Delta k \sum r^2 \ln R_c = \sum r \left(N - N_o q \right) \\ \Delta N_o \sum qr \ln R_c + N_o \Delta \alpha \sum r^2 \ln R_c - N_o \alpha \Delta k \sum \left(r \ln R_c \right)^2 = \sum r \left(N - N_o q \right) \ln R_c, \end{cases}$$

$$(4.42)$$

the solution of which ΔN_o , $\Delta \alpha$, and Δk determines the next approximation of the parameters

$$N_o^{(1)} = N_o^{(1)} + \Delta N_o; \qquad \alpha^{(1)} = \alpha^{(0)} + \Delta \alpha; \qquad k^{(1)} = k^{(0)} + \Delta k.$$
(4.43)

This cycle of operations is repeated for subsequent approximations until stable values of the parameters N_o , α , k are obtained. The results of the calculations are shown in Figs. 4.99 and 4.100 by solid curves for all the recording channels: total intensity of the standard 2NM-IQSY, multiplicities m = 1, 2, 3, 4, 5, and a lead-free neutron monitor 3SND.

The successive approximation method, proved convergent only for multiplicities $m \ge 6$, which is explained by the low statistical accuracy of measurement of higher multiplicities. For comparison, the calculated curves in Fig. 4.101 are normalized at $R_c = 0$.

Table 4.13 presents the parameters, as well as the maximal values of the coupling coefficients W_{max} and corresponding values of the rigidities R_{max} .

The polar coupling coefficients calculated according to Eq. 4.30 with parameters listed in Table 4.13 are shown in Fig. 4.102.



Fig. 4.101 The same as in Figs. 4.99 and 4.100, but normalized at $R_c = 0$ (According to Aleksanyan et al., 1985)

Table 4.13 The parameters N_o , α , k as well as the maximal values of the coupling coefficients W_{max} , and corresponding values of the rigidities R_{max} for different channels of CR registration onboard r/v *Academician Kurchatov* (According to Aleksanyan et al., 1985)

Channel	$N_o (\mathbf{h}^{-1})$	α	k	R_{\max} (GV)	$W_{\rm max}~(\%/{\rm GV})$
2NM-IQSY	42,930	8.32	0.866	4.76	4.55
3LND	59,076	6.55	0.800	3.80	4.99
m = 1	28,592	7.16	0.808	4.21	4.58
m = 2	4,481.8	10.26	0.951	5.43	3.99
m = 3	1,055.5	13.48	0.978	6.96	3.76
m = 4	325.63	20.30	1.060	9.15	3.23
m = 5	63.56	42.8	1.291	11.77	3.30

Fig. 4.102 Polar coupling coefficients calculated according to Eq. 4.30 with parameters listed in Table 4.13 for NM without lead-3LND, for 2NM-IQSY total intensity as well as for multiplicities m = 1, 2, 3, 4, and 5 (From Aleksanyan et al., 1985)



The measurements give the form of multiplicity distribution as the following:

$$N_m = b \exp\left(-gm^\delta\right),\tag{4.44}$$

where N_m is the number of cases of recording of multiplicity *m*; *b*, *g*, and δ are the parameters of distribution function. As an example, let us consider a particular case of the use of multiplicities 1, 2, and 4; in this case, it is easy to obtain explicit expressions for determining the parameters of distribution function:



Fig. 4.103 Dependencies of parameters δ and *b* from *g* (From Aleksanyan et al., 1985)

$$\delta = \ln \left[\ln \left(N_2 / N_4 \right) / \ln \left(N_1 / N_2 \right) \right] / \ln 2, \ g = \ln \left(N_1 / N_2 \right) / \left(2^{\delta} - 1 \right), \ b = N_1 \exp \left(g \right).$$
(4.45)

Results are shown in Fig. 4.103.

From Fig. 4.103 it follows that these parameters are functionally connected with one another; in this case:

$$g = (1.87 \pm 0.01) \delta^{1.226 \pm 0.008}, \ b = (5.77 \pm 0.04) \times 10^4 \exp\left(g\left(0.81 \pm 0.01\right)\right).$$
(4.46)

This means that a change in the cutoff rigidity leads to an interdependent change in the multiplicity distribution parameters. The dependencies of these parameters on the geomagnetic cutoff rigidity are shown in Fig. 4.104.



4.10 CR Latitude-Altitude Surveys and Secondary CR Dependencies from Cutoff Rigidity and Atmospheric Depth

2

4

0

6

8 10

 R_c (GV)

14

12

4.10.1 Latitudinal and Altitudinal Coupling Coefficients: Nominations and Interconnections

In Belov et al. (1987b), on the basis of CR latitude-altitude surveys the dependencies of the variations in secondary CR on geomagnetic cutoff rigidity and on the atmospheric depth of observation point are studied. The entire diversity of the properties of variations observed on the earth in any of the secondary CR components in the case of isotropic variations of the primary CR, may be reduced to two dependencies: on latitude and on altitude. These dependencies are determined by latitudinal (ω) and altitudinal (β) coupling coefficients. Most frequently, the latitude and altitude dependencies appear to be temporal. At the same time, the observed CR variations may also be due to the actual changes in geomagnetic latitude or in altitude (expedition measurements, airborne, and balloon-borne observations). Besides, the latitude dependence may take the form of variations of geomagnetic origin, while the altitude variation can be confused with barometric effect. The dependencies get evident when comparing among all types of the variations of extraatmospheric origin observed at different geomagnetic latitudes and atmospheric depths, as well as among the respective acceptance factors. The altitudinal coupling coefficient (or barometric coefficient, see details in Dorman, 1972a, M2004)

$$\beta(R_{\rm c}, h_o) = \left(\frac{\partial N(R_{\rm c}, h_o)}{\partial h_o}\right) / N(R_{\rm c}, h_o) \tag{4.47}$$

is a quantitative characteristic of the altitude dependence of secondary CR intensity $N(R_c, h_o)$. Similarly, the latitude dependence is characterized by the latitudinal coupling coefficient

$$\omega(R_{\rm c},h_o) = -\left(\frac{\partial N(R_{\rm c},h_o)}{\partial R_{\rm c}}\right)/N(R_{\rm c},h_o). \tag{4.48}$$

The latitudinal coupling coefficient $\omega(R_c, h_o)$, contrary to the conventional coupling function $W(R, R_c, h_o)$, is independent of the primary CR rigidity spectrum. The relationship between the latitude and altitude dependencies of the secondary CR intensity obtain evidence from the relation

$$\frac{\partial \beta \left(R_{\rm c},h_{o}\right)}{\partial R_{\rm c}} = \frac{\partial}{\partial R_{\rm c}} \left(\frac{\partial}{\partial h_{o}} \ln N(R_{\rm c},h_{o})\right) = \frac{\partial}{\partial h_{o}} \left(\frac{\partial}{\partial R_{\rm c}} \ln N(R_{\rm c},h_{o})\right) = -\frac{\partial \omega \left(R_{\rm c},h_{o}\right)}{\partial h_{o}}.$$
(4.49)

The dependence on R_c enters explicitly, and the dependence on h_o through only the coupling functions, the expression for the variation of the secondary CR

$$\delta(R_{\rm c},h_o) \equiv \frac{\Delta N(R_{\rm c},h_o)}{N(R_{\rm c},h_o)} = \int_{R_{\rm c}}^{\infty} \frac{\Delta D(R)}{D(R)} W(R,R_{\rm c},h_o) \,\mathrm{d}R.$$
(4.50)

By analogy with the determination of the barometric coefficients and the coupling functions, we introduce the quantitative characteristics of the altitude and latitude dependencies of $\delta(R_c, h_o)$, of integral multiplicity $m(R, h_o)$ and of $\Delta N(R_c, h_o)$:

$$\beta_{\delta}(R_{\rm c},h_o) = \frac{\partial}{\partial h_o} \left(\ln \delta(R_{\rm c},h_o) \right); \quad \omega_{\delta}(R_{\rm c},h_o) = -\frac{\partial}{\partial R_{\rm c}} \left(\ln \delta(R_{\rm c},h_o) \right), \quad (4.51)$$

$$\beta_{\Delta}(R_{\rm c},h_o) = \frac{\partial}{\partial h_o} \left(\ln \Delta N(R_{\rm c},h_o) \right); \quad \omega_{\Delta}(R_{\rm c},h_o) = -\frac{\partial}{\partial R_{\rm c}} \left(\ln \Delta N(R_{\rm c},h_o) \right), \tag{4.52}$$

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$$\beta_{\omega}(R_{c},h_{o}) = \frac{\partial}{\partial h_{o}} \left(\ln \omega \left(R_{c},h_{o} \right) \right); \quad \omega_{\omega}\left(R_{c},h_{o} \right) = -\frac{\partial}{\partial R_{c}} \left(\ln \omega \left(R_{c},h_{o} \right) \right), \quad (4.53)$$
$$\beta_{m}\left(R,h_{o} \right) = \frac{\partial}{\partial h_{o}} \left(\ln m\left(R,h_{o} \right) \right). \quad (4.54)$$

4.10.2 Latitude Dependence of Secondary CR Variations

Using Eqs. 4.50 and 4.51, we can easily obtain the explicit expression for the latitude dependence of the variation:

$$\frac{\Delta D(R)}{D(R)}\Big|_{R=R_{\rm c}} = \delta(R_{\rm c}, h_o) + \frac{\partial \delta(R_{\rm c}, h_o)/\partial R_{\rm c}}{\omega(R_{\rm c}, h_o)}.$$
(4.55)

Thus, by measuring a secondary variation and its variable with respect to R_c , we can obtain the primary variation for particles with rigidity $R = R_c$. The slope of the rigidity spectrum of the primary variation is due to the latitude dependence on $\delta(R_c, h_o)$, rather than to the value proper. From Eq. 4.55 it follows that

$$-\frac{\partial \left(\Delta D(R)/D(R)\right)}{\left(\Delta D(R)/D(R)\right)\partial R}\bigg|_{R=R_{c}} = \omega_{\delta}(R_{c},h_{o}) - \frac{\omega_{\delta}\omega_{\omega} + \partial\omega_{\delta}(R_{c},h_{o})/\partial R_{c}}{\omega(R_{c},h_{o}) + \omega_{\delta}(R_{c},h_{o})}.$$
 (4.56)

Figure 4.105 shows, as calculated in Belov et al. (1987b), latitude dependencies of the neutron component variation during solar minimum at altitudes with air



Fig. 4.105 Latitude dependencies of the neutron component variation during solar minimum at altitudes with air pressures 1,000 and 600 mb for different spectral indices γ of the power-law spectrum of primary CR variation (According to Belov et al., 1987b)

pressures 1,000 and 600 mb for different spectral indices γ of the power-law spectrum of primary CR variation $\Delta D(R)/D(R) \propto R^{-\gamma}$. The known form of coupling functions was approximated by the Dorman function (Eqs. 4.29 and 4.30) with parameters $\alpha = 6.95$ and k = 0.84 at $h_o = 1,000$ mb, $\alpha = 6.67$ and and k = 1.06 at $h_o = 600$ mb. From Fig. 4.105 it is seen that the position of $\omega_{\delta}(R_c, h_o)$ maximum is different at different values of γ , which is of importance when finding the primary variation spectrum.

4.10.3 Altitude Dependencies of Secondary Variations

The altitude dependence of a variation is determined primarily by the altitude behavior of the coupling functions. By definition,

$$\beta_{\delta}(R_{\rm c},h_o) = \frac{\partial \delta(R_{\rm c},h_o) / \partial h_o}{\delta(R_{\rm c},h_o)} = \beta_{\omega}(R^*,h_o), \qquad (4.57)$$

where $R^* > R_c$ is the effective rigidity depending on the primary variation spectrum (Belov et al., 1985, 1986). The relevant analysis shows that $\beta_{\delta}(R_c, h_o)$ is of the same sign, but of much smaller value, as the total barometric coefficient. Still, this value is quite sufficient so that substantial differences occur in the CR neutron component variations at different altitudes. If, for example, a 10% deep Forbush effect is observed, the difference in the hourly means of the neutron monitor counting rates at a 10–30 mb difference in altitudes will already exceed the statistical r.m.s. error. If a CR burst of the same value occurs, the altitude difference may be two to three times as small. In many cases, the barometric effect causes statistically significant changes in the observed variations (Belov and Dorman, 1980). At mountains, the altitude dependence of secondary variation is less pronounced than at sea level.

4.10.4 Determination of the Spectrum of the Primary CR Variations

Figure 4.106 shows $\omega_{\delta}(R_c, h_o)$ and $\beta_{\delta}(R_c, h_o)$ in dependence of γ at $R_c = 1,3$, and 15 GV at the level $h_o = 1,000$ mb. Substantial differences in the behavior of $\omega_{\delta}(R_c, h_o)$ and $\beta_{\delta}(R_c, h_o)$ can be seen. The variational barometric coefficient is most sensitive to the spectral slope changes in the domain of hard spectra, while the latitude coefficient $\omega_{\delta}(R_c, h_o)$ is a stronger function of γ for soft spectra.

From Fig. 4.106 it can be seen that in the case of the neutron component, considering the planetary distribution of cutoff rigidities and the altitude locations of CR stations, the latitude dependence of the variation may be regarded as more important than the altitude dependence. In the case of harder components, however, the altitude dependence becomes of greater importance.



Fig. 4.106 The dependencies of ω_{δ} (left scale) and β_{δ} (right scale) from the index of primary CR variation γ at $R_c = 1,3$, and 15 GV at the level $h_o = 1,000$ mb (According to Belov et al., 1987b)

Bearing in mind that the CR variations observed on earth contain not only isotropic but also other variations, we can expect that the actual latitude and altitude dependencies will differ from the patterns discussed above. For example, the superposition of two types of variations will substantially complicate the pattern, namely, the coefficients $\omega'_{\delta}(R_c,h_o)$ and $\beta'_{\delta}(R_c,h_o)$ may be of different form compared with $\omega_{\delta}(R_c,h_o)$ and $\beta_{\delta}(R_c,h_o)$ and their sign may change with altitude and cutoff rigidity. In practice, the complicated pattern of the observed altitude and latitude variations is most frequently indicative of a superposition of two or more types of primary CR variations, rather than of a complicated energy spectrum of a primary variation. In some cases, the primary CR variation spectrum will be found to be more effective by studying the latitude or altitude dependence of a secondary CR variation instead of using the acceptance coefficients calculated for prescribed spectral forms. With this approach, all the variations observed by detectors of the same type must be reduced either to a single atmospheric level h_{oo} or to a single cutoff rigidity R_{co} :

$$\delta' = \delta \exp\left(-\int_{R_{c}}^{R_{co}} \omega_{R_{c}} dR_{c}\right); \ \delta' = \delta \exp\left(-\int_{h_{o}}^{h_{oo}} \beta_{\delta} dh_{o}\right).$$
(4.58)

A dependence for finding a spectrum must be selected allowing for the type of observed component, for the latitude and altitude intervals of observations, and for the $\omega_{\delta}(R_{c}, h_{o})$ and $\beta_{\delta}(R_{c}, h_{o})$ in the properties discussed above.

4.11 The Latitude Knee of Secondary CR

4.11.1 The Latitude Knee of Secondary CR and its Origin

The CR latitude knee in the low cutoff region exists for every CR secondary component latitude curve, and above the knee the latitude curve has a plateau. The knee is defined to be that position of the cutoff value R_{ck} , where with a decreasing of latitude, the constant intensity drops and becomes latitude-dependent. The existence of the CR latitude knee has been known since the latitude surveys carried out by ionization chambers and described in Compton and Turner (1937). In Dorman (1954c) it was shown that for the latitude effect and the position of knee of the CR muon component is important to make corrections for the temperature effect; after these corrections, the position of the knee was determined as corresponding to $R_{ck} \approx 6-7$ GV. According to Dorman (1954c), from this result it followed that primary CR particles with rigidity smaller than 6–7 GV could not produce muons that arrived at sea level and detected by an ionization chamber shielded with 10 cm Pb.

In Allkofer and Dau (1969, 1970), theoretical calculations are presented for the latitude knee of secondary CRs; it is pointed out that two latitude knees exist at different positions: one for the nucleonic and one for the muon component. The existence of the CR latitude knee is caused by the influence of the geomagnetic field on the primary particles. The exact position of the knee, however, in the case of the nucleonic component is due to the flattening of the integral primary spectrum in the low-energy region. Concerning the latitude knee of the muon component, the position is determined by the minimum primary energy for the production of relevant muons as well as by the ionization loss of the muons in the atmosphere. The behavior of the latitude knee is calculated depending on the detected secondary particles energy and atmospheric depth.

4.11.2 The Calculation Model of the Secondary CR Knee Position

In the calculation model of the secondary CR knee position developed by Allkofer and Dau (1969, 1970), the following was supposed:

1. The integral primary particle spectrum for mean modulation has been expressed by the analytical formula

$$I(>E_{\rm ko}) \propto (E_{\rm ko} + B)^{-1.7},$$
 (4.59)

where E_{ko} denotes the kinetic energy of primary CR particles per nucleon (in GeV/nucleon) and *B* is the solar activity phase factor (main value of B = 2.4 GeV/nucleon).

2. The nucleon–nucleus interaction is regulated by the conception of the leading baryon.

- 3. Mean nucleon–nucleus interaction length in air is 74.5 g/cm^2 .
- 4. Mean total inelasticity $K_{\rm T} = 0.44$.
- 5. Mean pion inelasticity $K_{pi} = 0.35$.
- 6. Only muons from the decay of pions are considered.
- 7. Mean number $n_{\pi}(E_{ko})$ of charged pions produced in all directions at collision is described by

$$n_{\pi}(E_{\rm ko}) = 1.8 \times E_{\rm ko}^{1/4}.\tag{4.60}$$

8. The energy loss of muons in the atmosphere is 2 MeV/g.cm^2 .

4.11.3 The Latitude Knee of the Nucleonic Component at Sea Level

Main results of calculation based on the model described in Section 4.11.2 are shown in Fig. 4.107 for the detection of secondary nucleons and muons of different energies at sea level. The vertical nucleonic intensity for a fixed energy at sea level was calculated depending on the geomagnetic cutoff R_c . This procedure was carried out for different nucleon energies. In Fig. 4.107, the position of the knee, characterized by the geomagnetic cutoff R_{ck} , is plotted against the energy of the nucleons concerned. The position of the knee moves toward greater cutoff values with increasing kinetic energy E_k of the secondary nucleons detected. This behavior is a consequence of the following fact: The minimum energy of the primary particles required for the production of a nucleon of E_k at sea level increases with increasing



Fig. 4.108 The relative differential nucleonic intensity (nucleons of energy $E_k = 0.3 \text{ GeV}$) at sea level in the function of the geomagnetic cutoff R_c for different values of the phase factor B in the primary spectrum (Eq. 4.59) (From Allkofer and Dau, 1970)



of primary nucleon energy E_{ko} . For direct comparison of the calculated knee with neutron monitor measurements, it would be necessary to integrate the differential intensity taking into account the energy and zenith angle response as well as the multiplicity for neutron production separately for protons and neutrons. However, we are more interested in the knee of the differential energy and its behavior.

The arrow N on the abscissa axis of Fig. 4.107 denotes the position of the latitude knee of the vertical nucleonic intensity as derived from measurements on METEOR in 1965/1966 (Allkofer et al., 1969). From a comparison of the calculated curve in Fig. 4.107 with the measured knee position, it is concluded that nucleons of energy $E_{\rm k} = 0.3 \,\text{GeV}$ may be taken as typical for a neutron monitor.

In Fig. 4.108, the latitude curve for the vertical intensity of nucleons with $E_k = 0.3 \text{ GeV}$ is represented for three values of the phase factor *B*, in the primary spectrum.

From Fig. 4.108 it can be seen that with an increasing value of B, the latitude knee moves toward higher cutoff rigidities R_c . For B = 0, we get a pure power law spectrum for the primaries and, as can be seen, no knee for the secondary nucleon component at sea level. According to Allkofer and Dau (1969, 1970), Fig. 4.107 and 4.108 are quoted to explain the latitude knee of the nucleonic component: in general, the knee is caused by the influence of the geomagnetic field; the position of the knee, however, is determined by the flattening of the primary spectrum, characterized by parameter *B*, in the low energy region; primary particles with rigidities

below 2 GV practically do not contribute to 0.3 GeV nucleons at sea level, i.e., they do not contribute to the intensity of a neutron monitor. The knee of the nucleonic intensity is also altitude-dependent (see Section 4.11.5).

4.11.4 The Latitude Knee of the Muon Component at Sea Level

The position of the muon latitude knee in dependence of particle energy was calculated in an analogue procedure as described for the nucleons in Section 4.11.3. The calculated position of the muon knee was plotted against the particle energy in Fig. 4.107. With increasing muon energy, the knee moves only slowly toward greater cutoff values R_{ck} . The mean muon energy typical for standard meson monitors (10 cm Pb absorber) is of the energy $E_k = 0.4 \text{ GeV}$ (momentum p =0.5 GeV/c). According to Fig. 4.107, even for muon energies E_k greater 0.17 GeV (p = 0.24 GeV/c), the position of the muon knee is greater than a cutoff Rck of 3.5 GV. In consequence, the muon knee refers to cutoff rigidities Rck about twice as great as for the nucleonic knee. The arrow M in Fig. 4.107 denotes the region of the muon knee as derived from measurements. In general, one can conclude that primaries of rigidities smaller than 4 GV do not contribute to the intensity of meson monitors at sea level.

The influence of the phase factor *B* and the energy loss ε of the muons on the knee position at sea level are demonstrated in the latitude curves of Fig. 4.109 for 0.5 GeV/c muons. Curve 1 represents the actual case with B = 2.4 and $\varepsilon = 2 \text{ MeV/g.cm}^2$; the knee in this calculation being at a rigidity of 4.0 GV. Taking a pure power law spectrum for the primaries (B = 0), curve 2 will be obtained with the latitude knee at 2.9 GV. This position is now due only to the ionization loss ε of muons in the atmosphere. Otherwise, if the flattening primary spectrum (B = 2.4) is taken into account and no energy loss for muons ($\varepsilon = 0$) is assumed, curve 3 is obtained with a knee position at $R_{ck} = 1.2 \text{ GV}$. In curve 4 (B = 0, $\varepsilon = 0$), the knee is determined by the minimum primary energy which is necessary for the production of 0.5 GeV/c muons. From these considerations, we can conclude that in the actual case the latitude knee of muons is mainly determined by the energy loss ε and in the second place by the minimum primary production energy for muons. The knee of the muon intensity (muon momentum 0.5 GeV/c) is also altitude-dependent (see Section 4.11.5).

4.11.5 The Altitude Dependence of the Knee for Nucleonic and Muon Components

With increasing altitude, the position of the knee moves toward smaller cutoff values R_{ck} , as is shown in Fig. 4.110. This behavior is due to the fact that, with increasing altitude, a smaller minimum energy of the primaries is needed than at sea level to produce secondary CR particles of the same energy.

Fig. 4.109 The relative differential muon flux (momentum 0.5 GeV/c) at sea level in the function of the cutoff Rc for various values of muon energy loss ε and phase factor B: curve $1 - B = 2.4 \,\mathrm{GeV/nucleon},$ $\varepsilon = 2 \,\mathrm{MeV/g.cm^2}$ (actual case); curve 2 - B = 0, $\varepsilon = 2 \text{MeV/g.cm}^2$; curve $3 - B = 2.4 \,\mathrm{GeV/nucleon},$ $\varepsilon = 0$; curve 4 - B = 0, $\varepsilon = 0$. Vertical rows show expected positions of knee (in GV) (According to Allkofer and Dau, 1970)



Fig. 4.110 The position of the latitude knee R_{ck} in the function of the altitude for nucleons and muons (According to Allkofer and Dau, 1970)

4.12 Comparison with Observations on the CR Latitude Knee

4.12.1 Comparison for Neutron Component

In Table 4.14, the rigidities of the knee R_{ck} from various NM latitude surveys are compiled. For determination of the latitude knee in Allkofer and Dau (1970), only latitude surveys have been used, where counting rates of neutron monitors are available in terms of trajectory calculated cutoff rigidities. The knee of the nucleonic component is situated at about 2 GV.

The measured values of R_{ck} are in good agreement with the results of the abovedescribed calculations of Allkofer and Dau (1970).

In Fig. 4.111 results are shown of Simpson (1951) neutron component latitude surveys from December 13, 1947 up to October 31, 1949 on an airplane at altitudes of 30,000 ft (25.8 cm Hg air pressure; curve A) and 27,000 ft (22.5 cm Hg; curve B).

From Fig. 4.111 it can be seen that by increasing the altitude, the latitude knee moved to a higher geomagnetic latitude (to smaller cutoff rigidity), in agreement with the results of Allkofer and Dau (1970) shown in Fig. 4.110.

4.12.2 Comparison for Muon Component at Sea Level

In Table 4.15, the rigidity R_{ck} of the muon knee for various measurements are presented. The position of the knee was recalculated from the known geographical routes and geomagnetic latitude using the table of Kondo and Kodama (1965) for trajectory-calculated cutoffs.

As we noticed above, the measured latitude knee of the muon component is a result of the geomagnetic latitude curve and, in addition, the atmospheric latitude effect (Dorman, 1954c). However, according to Allkofer and Dau (1970), it was almost impossible to eliminate the atmospheric effect from the measured effect in order to get the geomagnetic effect which can be compared with the above-described calculations. The mean value for the rigidity $R_{\rm ck}$ of the muon knee at sea level

Expedition	Time	Atmospheric depth	Position of the knee $R_{\rm ck}({\rm GV})$
Rose et al. (1956)	1954/55	Sea level	2.2
Coxell et al. (1966)	1958/60	$680 \mathrm{g/cm^2}$	2.2
Carmichael et al. (1965)	1965	Sea level	2.0
Allkofer et al. (1968)	1965/66	Sea level	2.2
Kodama and Ohuchi (1967)	1966/67	Sea level	2.0

Table 4.14 Cutoff values R_{ck} of the knee of the nucleonic component near sea level (values of R_c were used from the trajectory calculations of Shea and Smart, 1967) (According to Allkofer and Dau, 1970)



Fig. 4.111 Latitude-dependence of fast neutron fluxes at altitudes of 30,000 ft (25.8 cm Hg air pressure; curve A) and 27,000 ft (22.5 cm Hg; curve B). Several points lie off the curve between 20° and 40° owing to errors in navigation. The family of curves at high latitude for B (27,000 ft) shows the change in intensity between October 27–31, 1949 (According to Simpson, 1951)

Table 4.15 Cutoff rigidity R_{ck} of the knee of the CR hard component at sea level. The position of the knee was in earlier times usually expressed in terms of the conventional geomagnetic latitude λ . After reconstruction of the routes of the various expeditions, the cutoff rigidity R_{ck} of the knee was estimated using the table of Kondo and Kodama (1965) (According to Allkofer and Dau, 1970)

Expedition	Time	Detector arrangement	Position of the knee
Skorka (1958)	1956/57	Twofold coincid. telescope, 2 cm Pb absorber	outbound voyage: $\lambda = 52^{\circ} \text{ S}, R_{ck} = 6 \text{ GV}$
			homeward voyage: $\lambda = 33^{\circ}$ S, $R_{ck} = 6$ GV, $\lambda = 43^{\circ}$ N, $R_{ck} = 5.5$ GV
Rose et al. (1956)	1954/56	Threefold coincid. telescope, 12.5 cm Pb absorber	Labrador: $\lambda = 42.5^{\circ}$ N, $R_{ck} = 4$ GV, $\lambda = 55^{\circ}$ N, $R_{ck} = 4$ GV $Atka: \lambda = 40^{\circ}$ S, $R_{ck} = 5$ GV
Dau and Weber (1966)	1966	Twofold coinc. telesc., 10 cm Pb absorber	$R_{\rm ck} = 5{\rm GV}$
Compton and Turner (1937)	1936/37	Ionization chamber, 12 cm Pb absorber	$\lambda = 38^{\circ} \text{ N},$ $R_{\text{ck}} = 6.5 \text{ GV},$ $\lambda = 35^{\circ} \text{ S}, R_{\text{ck}} = 6.5 \text{ GV}$

according to Table 4.15 amounts to about 5 GV which is sufficiently lower than it was determined in Dorman (1954c) by taking into account the latitude atmospheric effect ($R_{ck} \approx 7 \text{ GV}$). Let us note that it was only in Compton and Turner (1937), that an approximate correction of experimental data on the latitude atmospheric effect on the basis of ground temperature was made (see bottom row in Table 4.15), and they obtained $R_{ck} = 6.5 \text{ GV}$, about the same as was obtained in Dorman (1954c) on the basis of the integral method accounting the vertical distribution of air temperature (about this method, see in Dorman, M2004). Therefore, let us consider the results of Compton and Turner (1937) in more detail.

According to Compton and Turner (1937), records of CR intensity obtained by an ionization chamber with 12 cm Pb absorber on the ship *Aorangi* during 12 voyages between Vancouver (Canada) and Sydney (Australia) from March 17, 1936 to January 18, 1937, are used for investigation of the CR latitude effect and determining of the position of the latitude knee. In Fig. 4.112 CR latitude curves are shown for each voyage grouped into seasons.

The observed minimum of CR intensity near the equator averages 10.3% less than the intensity at Vancouver, in satisfactory agreement, considering the difference in experimental conditions, with earlier measurements. The critical latitudes, above which changes in intensity are less rapid, are found to be 38.4° N and 34.2° S, and beyond these latitudes the intensity is found to continue to increase with latitude. At the higher latitudes a variation is observed which appears to be seasonal, with the maximum intensity in the cold months in both hemispheres; this variation is closely correlated with the atmospheric temperature (see Figs. 4.113 and 4.114).

Compton and Turner (1937) concluded that the latitude effect curves, as thus corrected in Fig. 4.114, should show the effect of the earth's magnetic field alone. The latitude curves are now nearly flat beyond the critical latitudes and show a magnetic latitude effect of about 7.2%. This implies that a latitude effect of about 3.1% owes its origin to the atmospheric barrier. Seasonal variations in the corrected latitude effect curve are almost eliminated. Geomagnetic analysis of the energy distribution of the CR indicates a prominent component with a sharp energy threshold of about 7.5 GeV.

4.12.3 Comparison with Experimental Data on the CR Muon Latitude Knee at an Atmospheric Depth of 310g/cm²

At an atmospheric depth of 310 g/cm^2 , Neher (1957) performed latitude measurements by means of a GM counter telescope with a lead absorber. He established a latitude survey for particles penetrating 10 cm Pb as well as for particles penetrating 20 cm Pb, i.e., a latitude survey for incident muons of different mean energies. Looking at his results we find that the knee for muons penetrating 20 cm Pb is situated at lower latitudes than the knee for muons penetrating 10 cm Pb. The behavior of the knee in Fig. 4.107 with respect to the muon energy is confirmed by these experimental results. During two meridian flights at 115° W and 80° W, Neher (1957) found



Fig. 4.112 CR latitude curves for each voyage grouped into seasons (According to Compton and Turner, 1937)

the position of the knee at geomagnetic latitudes $\lambda = 50^{\circ}$ N and 49° N, respectively. In this experiment, the particles penetrated 11 cm Pb in a GM counter telescope at 310g/cm^2 atmospheric depth. Recalculating the knee positions in terms of cutoff rigidities, it was found that for the knee, $R_{ck} = 2.8$ GV and $R_{ck} = 3.0$ GV. The altitude dependence of the muon knee in Fig. 4.110 is in qualitative agreement with this experiment.



Fig. 4.113 Latitude effect of CR muon curves for the various seasons (According to Compton and Turner, 1937)



Fig. 4.114 Magnetic (solid lines) and atmospheric (broken lines) CR muon latitude effect for the four seasons. The sum of these two curves gives observed total effect shown in Fig. 4.112 (According to Compton and Turner, 1937)

4.13 South African Latitude Surveys at Different Altitudes by Airplanes

4.13.1 South African Expeditions, Response Functions and 22-Year Modulation

According to Stoker (1995), the CR latitude surveys were conducted every 2–3 years from 1962 to 1976 by the South African Air Force. Raubenheimer and Stoker (1974) comprehensively calculated the omni-directional attenuation coefficient β (R_c , h, t) of the primary CR as a function of atmospheric pressure h in mm Hg, cutoff rigidity R_c and modulation time t, which is defined to be zero at CR maximum. They used the July 1971, and August 1969, neutron monitor recordings at 10–13 equally spaced pressure levels between 226 mm Hg (30,000 feet) and 706 mm Hg (2,000 feet) and at six constant cutoff rigidities, ranging from 3.07 to 14.23 GV in 1971 and at 4.90 and 8.32 GV in 1969. The Deep River neutron monitor count rates during these measurements were, respectively, 0.96 and 0.87 relative to that of the May 1965 solar minimum. This coefficient relates the measured count rate, N, to a reference count rate N_r (R_c , h_r , 0) at a reference pressure h_r (typically sea level) and time t = 0 of zero modulation at solar minimum:

$$N(R_{\rm c},h,t) = N_r(R_{\rm c},h_r,0) \exp\left(-\int_{h_r}^h \beta(R_{\rm c},h,t) \,\mathrm{d}h\right). \tag{4.61}$$

Stoker (1993) has accepted for $N_r(R_c, h_r, 0)$ the least-squares regression fitting of the Dorman function

$$N_r(R_c, 760, 0) = N_o\left(1 - \exp\left(-\alpha R_c^{-k}\right)\right)$$
(4.62)

to the latitude distribution of the 1976 sea-level survey of Potgieter et al. (1980) with $\alpha = 8.427$ and k = 0.8935 (Moraal et al., 1989). With $N_o = 100$ at sea level, $N(R_c, h, 1976)$ was determined from Eq. 4.61 at R_c from 3 to 15 GV at different pressure levels and the constants in Eq. 4.62 were obtained by regression fitting to these values (Table 1 in Stoker, 1994). Also, second-order polynomials in cutoff rigidity have been fitted to these values (Table 2 in Stoker, 1994). Both the 1976 curves in Fig. 4.115 are the Dorman function for $R_c < 4.5$ GV and the second-order polynomial for 4.5 GV for a better representation of the count rate distribution at 30,000 feet than given by either of these functions.

Note the clear deviation in the 5 min counts between 4.5 and 10 GV from the upper 1976 curve. The same deviation was noted on the other distributions except on the 1965 distribution of Keith et al. (1968). The cutoff rigidities of the count rates between 4.5 and 10 GV have been adjusted to fall on the (second) 1976 curve and the same adjustments in cutoff rigidities have been made to the other South African distributions. The curves to the other distributions in Fig. 4.115 have been derived by applying a modulation function to the differential of the 1976 Dorman/polynomial



Fig. 4.115 CR latitude distributions at 30,000 feet pressure altitude (From Stoker, 1995)

response function, which is the 1976 sea-level response function transformed to a 30,000 feet pressure altitude. These other curves were least-squares fitted to the respective distributions by varying the parameters of the modulation function. The modulation parameters for the fit of the uppermost curve to the 1965 distribution of Keith et al. (1968) were so small that there are very small differences between the differential response functions of 1965 and 1976, as depicted by the upper pair of curves in Fig. 4.116.

Figure 4.116 shows some of the differential response functions obtained from the regression curves in Fig. 4.115. The error bands on these functions were estimated according to the procedure described by Van der Walt (1983). Differential response functions, obtained by Moraal et al. (1989) from measurements at sea level during the previous four solar minimum epochs, are shown in Fig. 4.117.

These sea-level surveys showed a clear difference in differential response functions in consecutive solar minima: The 1954 and 1976 pair, as well as the 1965 and 1987 pair, agrees well, but the 1965 and 1987 CR spectra are significantly harder than the 1954 and 1976 spectra. This is in accord with the drift effects in modulation as described by Moraal et al. (1989). Pair (b) of Fig. 4.116 are differential response functions obtained from distributions recorded by NM- IGY and by NM-IQSY on the 1974 flights. From these response functions, the NM-IGY seems to be a little more sensitive to CR primaries of low rigidity than the 1NM-IQSY. It is significant that the 1954 (NM-IGY) and 1976 (NM-IQSY) sea-level results in Fig. 4.117 show a similar small difference. Taking this difference in response between NM-IGY and NM-IQSY into account, the 1954 and 1976 sea-level response functions appear to agree even better than perceived by Moraal et al. (1989). The response functions at



aircraft altitude for 1965 and 1976, pair (a) in Fig. 4.116, are opposite to those found for sea-level responses and contrary to the difference expected from drift effects. In order to rule out differences between recordings in the North American/Australian regions during 1965 (Keith et al., 1968) and the South African region, the 1966 distribution was demodulated to the 1965 solar minimum, using stationary neutron monitor recordings. It appears that these two differential response functions from airbome NM-IGY recordings are similar, as depicted by pair (c) in Fig. 4.116. It is therefore only necessary to correct the 1965 distribution of pair (a) to a NM-IQSY distribution, using the two 1974 curves. The bottom pair (d) shows that the 1965 and 1976 response functions are in agreement within experimental errors.

Stoker (1995) came to the following conclusions:

- The 1965 and 1976 response functions should be different according to the drift theory of modulation, but the accuracy of the aircraft surveys is insufficient to detect a difference at consecutive solar minima (pair d in Fig. 4.116). It is hard to correct, however, for short-term isotropic and anisotropic changes in primary CR intensities during an aircraft flight of 8–10 h. Sea-level surveys, on the other hand, are conducted over several months and are, therefore, much less affected by short-term anisotropic intensity variations.
- 2. After demodulating the 1966 distribution to the 1965 solar minimum epoch, the response function from this distribution in the Cape Town region agrees well with the function obtained from the 1965 North American/Australian recordings of Keith et al., 1968 (pair c in Fig. 4.116).
- 3. The NM-IGY appears to be more sensitive to primary CR of low rigidity than the NM-IQSY (pair b in Fig. 4.116).
- 4. The 1976 curves of Fig. 4.115 were obtained from the 1976 sea-level survey, which was conducted from Cape Town to New York and to the Fareast while the airborne 5 min counts with a deviation between 4.5 and 10 GV from the upper 1976 curve, were recorded only in the Cape Town region. This deviation was also noticed by König et al. (1977), in the 1976 CR survey on a westward flight, who could not explain it by deducing effective cutoff rigidities from trajectory tracings. The deviation of points improved slightly when asymptotic directions are computed from the trajectory code (Bieber and Evenson, 1992) based on the Tsyganenko (1989) magnetosphere model. It cannot be ruled out that an inclined incidence of CR in the Cape Town Magnetic Anomaly region caused this deviation at 30,000 feet pressure altitude.

4.13.2 Latitude Distributions of CR Components at Sea Level and at Airplane Altitudes in the South African Magnetic Anomaly

It is well known that the intensity of the horizontal component of the geomagnetic field reaches a local maximum value in a region slightly to the south of South Africa,

the region being known as the South African or Cape Town Magnetic Anomaly. Due to the fact that the trajectories of CR are highly influenced by the magnetic field they traverse, one would expect that this magnetic anomaly could have a strong effect on cosmic radiation.

According to Van der Walt et al. (1970), the CR latitude surveys, en route to Syowa Base, Antarctica from 1956 to 1962, showed a latitude knee at an unusual high cutoff rigidity during 1956/57, which developed into a double knee during later surveys. Shipboard NM observations conducted by the Potchefstroom group from 1962 to 1968 in the region of the South African Magnetic Anomaly, show normal latitude curves depending on the phase of the solar activity cycle when plotted against cutoff rigidities calculated from particle trajectory integrations. The latitude dependence of the CR nucleonic and soft components was also obtained during airplane flights in 1962, 1964, and 1966. These distributions are compared with CR distributions in the northern hemisphere. CR latitude surveys in the vicinity of South Africa were conducted before and during the IGY by Skorka (1958), Rothwell and Quenby (1958), Pomerantz et al. (1958), Kodama and Miyazaki (1957), and Kodama (1958). The measurements of Kodama and Miyazaki (1957), and Kodama (1958) were taken on board m/v Soya on the route Japan-Cape Town-Antarctica, and their results showed a higher intensity in the vicinity of South Africa than would normally be expected at these latitudes. They found the knee in the intensity-latitude curve in 1956/57 a small distance to the south of South Africa at 35°S geomagnetic latitude, and during two later surveys, they found the knee at approximately the same latitude (Fukushima and Kodama, 1961). Japanees scientists M. Kodama and others was the only group who measured the latitude distribution in a southerly direction from South Africa, but their results were supported to some extent by the measurements of Pomerantz et al. (1958) who found the CR intensity at the southern-most point of Africa only approximately 7% lower than that at a weakly developed latitude knee in the northern hemisphere. According to Van der Walt et al. (1970), the above-mentioned results of M. Kodama and others was surprising in view of the fact that the position of the latitude knee they found, corresponds to a cutoff rigidity of approximately 7 GV according to the centereddipole theory, whereas Simpson et al. (1956) found the latitude knee between 2 and 4 GV during six surveys. Consequently, it seemed as if either the centered-dipole cutoff rigidities were seriously in error or that the magnetic anomaly had a very large influence on cosmic radiation. Furthermore, in a comprehensive figure of several latitude surveys compiled by Rothwell (1958), it is conspicious that the intensities obtained by M. Kodama and others in the vicinity of South Africa and that obtained by Simpon et al. (1956) in the South Atlantic, were considerably higher than that obtained during other latitude surveys, showing that the modified cutoff rigidities of and Rothwell and Quenby (1958) could not explain the effects of the magnetic anomaly. Because of the unusual results obtained in the vicinity of South Africa, the Potchefstroom CR group decided in 1961 to investigate the effects of the South African Magnetic Anomaly on cosmic radiation. Early in 1962, research flights were undertaken from Cape Town at a pressure altitude of 10,000 feet in order to confirm the position of the latitude knee, which Kodama et al. (1962) found

at a mean geomagnetic latitude of 35.4° S during eight surveys. The most southerly geomagnetic latitude reached during the flights was 42° S, and the Potchefstroom CR group concluded from the measurements that no latitude knee existed north of 40.5° S geomagnetic latitude (Du Plooy et al., 1963). The last voyage of the m/v Soya to Antarctica took place in 1961/62. During this voyage, a double knee was found, one knee at 35° S and another at approximately 50° S geomagnetic latitude (Kodama et al., 1962). Kodama (1963) reanalyzed their previous voyages and found that the double-knee effect was already present in two previous voyages, and that the variation in solar activity probably caused this anomalous modulation effect in the magnetic anomaly. At this stage, the research vessel m/v RSA of the South African Department of Transport became available for CR latitude surveys during annual voyages from Cape Town to Antarctica, Marion Island, Gough Island, and Tristan da Cunha. Results of voyages from 1963 to 1968 are reported in Van der Walt et al. (1970). Research flights were undertaken in a Hercules C-130 aircraft of the South African Air Force in 1964 and 1966 at a pressure altitude of 30,000 feet, measuring the nucleon, meson, and soft components of cosmic radiation. NM-IGY (Simpson's type, modified to obtain a higher counting rate with a smaller setup) was installed onboard the m/v RSA late in 1962. In 1963, this apparatus was replaced by NM-IQSY, and in 1967 the registration system of the NM was replaced. The NM was sealed in a steel box and placed on the deck of the RSA. In order to eliminate effects due to the severe change in air temperature during voyages to the Antarctic region, the NM was thermostatically controlled. Furthermore, the thickness of the reflector of the NM-IQSY was increased to 20 cm in order to minimize effects on the counting rate due to changes in the environment of the NM. During the flights on board the Hercules in 1964, a Simpson-type two-counter NM was used, as well as a Geiger counter and four neutron counters with different thicknesses of paraffin wax (Van der Walt et al., 1965). During the flights in 1966, a smaller NM was added to the instrumentation, and it was placed in the front of the aircraft and approximately 5 ft higher than the large monitor in order to minimize effects due to secondary particles produced in the fuel of the aircraft. The results of the voyages of the years 1963–1968 are presented in Fig. 4.118. Averages of the 6-hourly counting rates over intervals of 0.2 GV are given in Fig. 4.118. Cutoff rigidities for the 6-hourly points were interpolated from $2^{\circ} \times 2^{\circ}$ grid values of cutoff rigidities, interpolated by Shea and Smart (1966) from trajectory-calculated values. The results have been corrected by means of a regression technique for small drifts in NM sensitivity during different voyages, probably due to changes in the extra high tension supply.

The annual intensity latitude curves in Fig. 4.118 have been normalized in such a way that the mean intensity at rigidities below 1.5 GV for the 1966 survey is 100. This corresponds to a counting rate of approximately 60,000 counts per hour. Furthermore, a correction was applied to the annual curves in order to get the same variation in mean intensity below rigidities of 1.5 GV as for the normalized mean intensity of the neutron monitors at Deep River, Ottawa, and Wilkes. This correction amounted to less than 2% for any year. The results of the 1964 airplane flights have been reported in Van der Walt et al. (1965). The loop at the low-rigidity end of



Fig. 4.119 NM results obtained during four flights in 1966 at 30,000 feet altitude. Each point represents a 4 min reading. Cutoff rigidities are according to Shea and Smart (1966). The results by Keith et al. (1968) are given by the broken line (From Van der Walt et al., 1970)

the NM latitude curves in 1964 was not observed under similar conditions in 1966. This result indicates that the loop has not been caused by energetic particles produced in the fuel of the aircraft. The NM results of the 1966 flights are presented in Fig. 4.119. In the discussion, Van der Walt et al. (1970) note that in Kodama (1968) the results of their previous latitude surveys are plotted against rigidity calculated by trajectory integration. In these curves the double-knee effect disappears and the latitude knee shifts from approximately 4.5 GV in 1956–1957 to 3 GV in 1961/62. Results of Van der Walt et al. (1970) at sea level show no significant shift of the latitude knee which is at a cutoff rigidity of approximately 2.5 GV. This is consistent with the theoretical calculation of the CR intensity-latitude curves by Allkofer and Dau (1969), which predict no observable shift in the sea-level latitude knee with varying solar activity.

Although the surveys of Kodama et al. (1962) were conducted during the phase of high mean solar activity, and the surveys of Van der Walt et al. (1970) mainly at the phase of low mean solar activity; results of Van der Walt et al. (1970) during 1968, which near to the solar activity maximum of the solar cycle, show no tendency of a shift of the latitude knee toward higher cutoff rigidities. Furthermore, the Van der Walt et al. (1970) surveys of 1965 and 1966 are in good agreement with the 1965/66 latitude survey of Carmichael and Bercovitch (1969b), and the results obtained by Kodama and Ohuchi (1968) during their survey on board the m/v FUJI also indicate the position of the latitude knee at approximately 2.5 GV in 1967/68. Van der Walt et al. (1970) therefore conclude that their sea level measurements revealed no unusual effect due to the South African Magnetic Anomaly.

The differential latitude response function is also a very sensitive indicator of deviations from a normal latitude distribution. Lockwood and Webber (1967) included the Potchefstroom CR group's 1964 airplane monitor results in their analysis of differential response functions for various atmospheric depths, and it is evident from their collective figure of differential response functions, that the curve derived from the Potchefstroom CR group's results fits satisfactorily into the complete picture. Furthermore, in Fig. 4.119, these 1966 airplane neutron monitor results are plotted against cutoff rigidities calculated by Shea and Smart (1966), and they show good agreement with those of Keith et al. (1968) obtained at the same pressure altitude. The results of both the Potchefstroom CR group's sea-level and airplane CR latitude measurements therefore lead to the conclusion that the cutoff rigidity calculated by Shea and Smart (1966) is a reliable parameter of CR intensity, even in the South African Magnetic Anomaly. The anomalous results of Kodama et al. (1962) were probably caused by effects due to large variations in CR intensity which are difficult to correct.

4.13.3 Cutoff Rigidities and Latitude Dependence of Muons at 307 g/cm² in Inclined Directions

According to Coetzee et al. (1970), in order to investigate computations of cutoff rigidities in inclined directions, narrow-angle meson telescopes, one vertical and four inclined, were flown during August 1966 from Cape Town in the magnetic north and south directions, at 26,000 and 30,000 feet pressure altitudes. The meson telescope consisted of five identical twofold coincidence liquid scintillators with 10 cm Pb absorbers. The photomultipliers were screened from the magnetic field of the earth and that generated by the electrical system of the aircraft. The discriminators were set to record only pulses from relativistic particles passing through the scintillators. The resolving time of the coincidence circuitry was 50 nsec, and accidental coincidences were negligible. The dimensions of the telescopes were

approximately the same as those of Biehl et al. (1949). The axes of the telescopes were directed at 45° to the vertical and magnetic east, south, west, and north azimuths. From a study of the distribution of particles recorded over the permitted zenith and azimuthal angles of telescopes (Lindgren, 1966), it appears that the distribution strongly peaks along the axis of the telescopes. Taking into account the variation of cutoff rigidity within the solid angle of the telescopes and the varying absorption effect of the atmosphere with zenith, Coetzee et al. (1970) concluded that, to a fair degree of accuracy, the effective cutoff rigidity is in the direction of the axis of these narrow angle telescopes. Cutoff rigidities for the inclined directions were computed using a method similar to that of McCracken et al. (1962), representing the earth's magnetic field by a sixth-order approximation according to Finch and Leaton (1957). This simulation of the earth's magnetic field appeared to give correct values for the vertical cutoff rigidity in the region of the Cape Town Magnetic Anomaly (Van der Walt et al., 1970). The main cone cutoff rigidities were calculated by a relatively small computer (IBM 1130) for 14 locations along the flight routes for the vertical and the four azimuth directions at zenith angles of 30° , 45° , and 60° . Inclined cutoff rigidities at some of these locations were also calculated by M. A. Shea for zenith angles of 16° , 32° , and 48° .

Because of the low recording intensity of the telescopes, the 4-min recordings were averaged over half-hourly intervals, during which time approximately 2° of latitude were covered. Even then the statistical scattering of the intensity was large, taking into account the small latitude effect of the CR hard component. In Fig. 4.120, the results of the vertical telescope at 307 g/cm2 (30,000 feet) and 366 g/cm2 (26,000 feet pressure altitude) are represented as a function of main cone cutoff rigidity.

Due to the statistical scattering of the points in Fig. 4.120, it was not possible to obtain the best-fitting curve to the experimental points at 307 g/cm2 without working from an acceptable differential intensity response curve. The differential intensity response curve V, in Fig. 4.121, yielded the curve P, in Fig. 4.120. This latitude curve may be compared with the curve Q + W obtained by Webber and



Fig. 4.120 The half-hourly averaged intensities of the vertical telescope at 307 and $366 \,\mathrm{g \, cm^{-2}}$ as a function of main cone cutoff rigidity (From Coetzee et al., 1970)



Fig. 4.121 The differential response curves for the vertical (V) and inclined intensities (From Coetzee et al., 1970)



Fig. 4.122 The intensities averaged for the four inclined telescopes. The latitude curves were deduced from the corresponding differential response curves in Fig. 4.121 (From Coetzee et al., 1970)

Quenby (1959) for muons at 30,000 feet pressure altitude, bearing in mind the difference between their, and the cutoff rigidities used in Coetzee et al. (1970).

Within the statistical scattering of the points, the four inclined directions give the same latitude effect when the intensities are plotted against the main cone cutoff rigidity. Half-hourly averaged intensities for all four inclined telescopes were averaged in groups of three with increasing main cone cutoff rigidity and are shown in Fig. 4.122. Curves 1, 2, and 3 are obtained accepting the corresponding differential intensity response curves in Fig. 4.121. The solid curve l gives an overall best-fit to the inclined intensity points, and in particular for the last pointing telescope. The intensity points of the west-pointing telescope tend to deviate from this curve, following curve 3, while the intensity points of the north and south-pointing telescopes tend to follow curve 2. These deviations are obvious only at medium rigidities, but they are not considered statistically significant.

Fig. 4.123 The difference between main cone and effective cutoff rigidities as a function of main cone cutoff rigidity for the southern and northern hemispheres (From Coetzee et al., 1970)



The results in Figs. 4.120–4.121 are represented as a function of main cone cutoff rigidity because the interpolation for intermediate locations could be done with more confidence from the main cone cutoff computations for inclined directions than from the much more thinly spaced effective rigidities calculated by M. A. Shea for locations along the flight routes. Figure 4.123 shows the differences between main cone and effective cutoff rigidities as calculated by Shea (1969) for the southern and northern hemispheres.

The differences appear to be larger for the southern Cape Town region than for the northern European region and a fine structure penumbral effect can also not be excluded. The results for the inclined telescopes have also been plotted as a function of the effective cutoff rigidity using Shea's computations for 48° zenith. The net result is within the statistical scattering the same as that for main cone cutoff rigidities (Fig. 4.122), as discussed above.

In a discussion of the obtained results, Coetzee et al. (1970) note that if side showers also contribute to the counting rates of the telescopes, the stronger vertical latitude distribution will effect the latitude distribution of the inclined telescopes. Since the cutoff rigidities at medium and low latitudes are less for the west-pointing than for the north-pointing and vertical telescopes, it will result in a steeper latitude distribution for this inclined direction. For the east- and south-pointing telescopes with larger cutoff rigidities than vertical at the same latitude, it will result in a flatter latitude distribution. If curve 3 in Fig. 4.122 were for the west-pointing

telescope, curve 2 for the north and south, and curve 1 for the east-pointing telescopes, then these deviations could be accounted for if 20% of the vertical intensity was also recorded by the inclined telescopes. However, according to Biehl et al. (1949) the contribution of side showers to the true telescope counting rate is negligible. The variation of the effective atmospheric temperature above 30,000 feet altitude was calculated along the flight routes and corrections were made according to Dorman (M1957). It was also found to be negligible for the latitude distributions.

Coetzee et al. (1970) came to the following conclusions:

- 1. Within the statistical uncertainty of the measurements, a coherent latitude distribution could be obtained both when the results of the four inclined telescopes were plotted against main cone cutoff rigidity and against effective cutoff rigidity.
- 2. The Finch and Leaton (1957) sixth-order approximation of the earth's magnetic field appears therefore sufficient for cutoff rigidity calculations in the region of the Cape Town Magnetic Anomaly.
- 3. More definite conclusions can only be made, however, if the statistical accuracy in the counting rates of the telescopes is improved.
- Detailed computations for cutoff rigidities in inclined directions will also be necessary.

4.14 Latitude CR Surveys on Balloons

4.14.1 Survey of CR Intensity in 86° N to 73° S Geomagnetic Latitude on Balloons

According to Van Allen (1994), during the 1957/58 International Geophysical Year, the University of Iowa undertook a total of 54 balloon-launched rocket ("rockoon") flights during two separate shipboard expeditions. The first expedition was aboard the US *Plymouth Rock* (LSD 29) from Norfolk, Virginia, to Thule, Greenland, and return to Norfolk, August 1–20, 1957. The second was aboard the US *Glacier* (AGB 4) from Boston, Massachusetts, to geographic latitude 72° S in the Ross Sea off the coast of Antarctica and then to Port Lyttleton, New Zealand, September 23 to November 10, 1957. As described in Van Allen and Gottlieb (1954; Van Allen, 1959), the rockoon technique provides an inexpensive means for delivering small (4–18 kg) scientific payloads to altitudes of the order of 120 km by launching the rockets at points above most of the atmosphere.

The paper by Van Allen (1994) describes the measurements of CR intensity during the ascent of the balloons on 26 flights in the geomagnetic latitude range 86° N to 73° S and up to altitudes of about 25 km. This survey was unique during the 1957 period of maximum solar activity. In this paper J. A. Van Allen returned to the original records to make a full reduction and summary of the data.

The basic detector in all flights reported in Van Allen (1994) was a cylindrical Victoreen 1B85 Geiger–Mueller (GM) tube of effective length $l = 6.60 \pm 0.2$ cm,

diameter $a = 1.91 \pm 0.02$ cm, and wall thickness 30 mg/cm2 (aluminum). The efficiency of a 1B85 for ground-level CR was measured in a conventional triple coincidence telescope and found to be $\varepsilon = 0.97 \pm 0.01$. In various flights, one, two, or three GM tubes were mounted in the upper end of the payload of the rocket, within a pressure-sealed aluminum nose cone of thickness 170 mg/cm2. The scaled counting rate of each tube was telemetered to a receiving station on the ship and the scaled pulses (scale of 8, 16, or 32) were recorded on the moving paper tape of a two-channel Brush oscillograph. The axes of the payload and the GM tubes were parallel to each other. During the balloon ascent, this common axis was tilted from the vertical by a nominal 10° . Baroswitches set to a nominal pressure of 35 mbar were used to connect a battery to the igniter of the Loki II rocket which was used in both 1957 expeditions. The laboratory calibration of these baroswitches gave a mean pressure altitude of 22.9 km, with standard deviation 0.3 km of individual values from the mean. In some cases, the rocket failed to fire and the open-neck polyethylene balloon with payload became a "floater" at its estimated ceiling altitude of about 25 km. The mean time of firing 30 rockets was 78.5 min after release, with standard deviation 2.5 min of individual values from the mean. The raw counting rates (usually summarized as 5-min averages) of a single GM tube (average of two or three in some cases) as a function of time for 26 flights during ascent are shown in the nine panels of Fig. 4.124 with explanatory captions. The approximate altitude can be read at any desired time by multiplying the time from release by 291 m/min. A different presentation of these data was obtained by reading the curves of Fig. 4.124 at times corresponding to altitudes of 10, 12.5, 15, and 20 km. The four resulting sets of counting rate data versus geomagnetic latitude are shown in Fig. 4.125. Northern and southern hemisphere data are combined in Fig. 4.125 inasmuch as there seemed to be no clearly credible difference between the data in the two hemispheres. The scatter of points associated with each of the four constant altitude curves is thought to fairly represent the composite uncertainty of the data for all causes.

In Fig. 4.125 the smooth curves are visual fits to the data.

The absolute omni-directional intensity J_o is derived from the counting rate N by the formula

$$J_o = N/(G\varepsilon), \tag{4.63}$$

where *G* is the omni-directional geometric factor. For a cylindrical tube of length *l* and diameter *a*, *G* is a weak function of the angular distribution of particle intensity. Precursory balloon work with similar apparatus showed that the angular distribution of the unidirectional intensity *j* of CR at $\lambda \approx 52^{\circ}$ N is of the form

$$j(\theta) = \begin{cases} j_o \cos^n \theta & \text{for } \theta \le \pi/2, \\ 0 & \text{for } \theta > \pi/2. \end{cases}$$
(4.64)

In Eq. 4.64 θ is the zenith angle and j_o is the value of j at $\theta = 0$; value *n* decreases from about 2 at sea level to 0 at altitudes corresponding to atmospheric depths of 28 g/cm2. In Eq. 4.64, particles traversing the sensor from the lower hemisphere are



Fig. 4.124 The raw counting rates of a single Geiger–Mueller tube as a function of time from the shipboard release of the balloon to the time of firing of the rocket (vertical arrows) in all cases in which such firing occurred. The absence of such an arrow means that the rocket did not fire or that the signal was lost during the balloon flight. In several of the latter cases, data are shown for the floating phase of the balloon's flight at its maximum altitude. The flights are grouped according to similar geomagnetic latitudes, north or south, with the curves in the same vertical order, as are the labels in the upper left-hand corner of each panel. Note the different vertical scales among the nine panels and the vertical offsets of the base lines in each panel as shown by the dashed horizontal lines. Panels **a**, **b**, **c**, **d**, **e**, **f**, **g**, **h**, **i**. (According to Van Allen, 1994)



Fig. 4.124 (continued)



Fig. 4.124 (continued)

implicitly assigned to the upper hemisphere. Hence, assuming azimuthal symmetry,

$$J_o = 2\pi \int_{0}^{\pi/2} j(\theta) \sin \theta d\theta.$$
(4.65)

According to Van Allen (1994), the geometrical factor *G* in Eq. 4.63 depends on the value *n* in Eq. 4.62 as following: for n = 0, 1, and 2 the corresponding G_o, G_1 , and G_2 are

$$G_o = \frac{\pi a l}{4} \left(1 + \frac{a}{2l} \right), \quad G_1 = \frac{2al}{3} \left(1 + \frac{\pi a}{4l} \right), \quad G_2 = \frac{3\pi a l}{16} \left(1 + \frac{a}{l} \right).$$
(4.66)

For the used values of l = 6.60 cm, a = 1.91 cm, $\varepsilon = 0.97$, and values of *n* considered above for different altitudes, the following values for geometrical factor were found on the basis of Eq. 4.66: 10.1 cm2 at altitude 10 km, 10.4 cm2 at 12.5 km, 10.7 cm2 at 15 km, and 11.0 cm2 at 20 km (these values of geometrical factor G were used in converting Figs. 4.125 and 4.126). The measurements include, without distinction,



the "soft" and "hard" components of the cosmic radiation within the atmosphere. The shielding of the sensitive volume of the detector was about 170 mg/cm2 of aluminum, corresponding to energy thresholds of 0.5 MeV for electrons or 10 MeV for protons.

The smooth curves in Fig. 4.125 were transformed to produce the family of four curves in Fig. 4.126 giving absolute values of omni-directional intensity as a function of $\pm \lambda$ at the four selected altitudes. Figure 4.126 is a representative summary of some of the experimental results, although it is evident that values of J_o at other altitudes can be derived in a similar manner from Fig. 4.125.

Van Allen (1994) came to the following conclusions:

- 1. Measurement of CR intensity within and above the atmosphere was a field of intensive research in the 1930s, 1940s, and 1950s (a valuable review of the subject with an extensive bibliography is that of Ray, 1961). The University of Iowa's essentially homogeneous body of observations with balloons and "rockoons" began in 1952 and continued through late 1957, thereby spanning an important segment of an 11-year cycle of solar activity as shown in Fig. 4.127.
- 2. The described 1957 latitude survey was at about the time of maximum solar activity. The absolute CR intensities (Fig. 4.126) are thought to have a durable reference value in characterizing that time period and possibly previous and subsequent periods of maximum solar activity during which interplanetary CR intensity has the minimum of its solar-modulated magnitude. A tabulation of the 1957 absolute values of J_o at the four selected altitudes of Fig. 4.126 and those in early 1953 at $\lambda = 52^{\circ}$ at the same altitudes is presented in Table 4.16.


Fig. 4.127 Monthly means of Climax NM rates 1953–1964 (upper curve) and monthly mean sunspot numbers 1950–1964 (lower curve, in inverted format) (According to Van Allen, 1994)

The ratio in the last column of Table 4.16 is labeled the solar modulation factor. Its value is 0.69 ± 0.04 , essentially the same at the four altitudes. The empirical significance of this factor is evident from Fig. 4.127, which shows the corresponding Climax NM factor to be 0.84 ± 0.02 .

Altitude (km)	Depth $(g cm^{-2})$	Epoch		Solar modulation factor		
		1953.3	1957.7			
10	277	1.06	0.72	0.68		
12.5	191	1.91	1.27	0.66		
15	129	2.65	1.82	0.69		
20	58	3.36	2.37	0.71		

Table 4.16 Comparison of the omni-directional CR intensities J_o (in cm⁻² sec⁻¹) at $\lambda = 52^{\circ}$ (According to Van Allen, 1994)

4.14.2 Latitude Surveys by Balloon Measurements of CR Vertical Intensity and East–West Asymmetry; Determining Energy Spectrum and Charge Sign of Primary CR

Winckler et al. (1950) noted that the measurements of the azimuthal distribution of the primary CR at latitudes near the geomagnetic equator, combined with measurements of the vertical flux over a range of latitudes, in principle, enables one to evaluate the energy spectrum and to determine the sign of the charge of the primary radiation over a range of energies from about 1 to at least 14 Gev. The majority of the experiments on which our knowledge of the geomagnetic behavior of CRs is based, deal almost entirely with secondary CRs generated in the atmosphere. To compare these data with extensive theoretical calculations of the motion of CR primary particles which have reached the earth from infinity, one must make assumptions which are difficult to test experimentally (the monograph of Montgomery, 1949 gives a survey of the literature and discussion of experiments on this subject up to 1948). It has become apparent that the magnitude of the various geomagnetic effects increases as the observations are extended to smaller depths in the atmosphere, and for some time it has been considered highly desirable to make observations at very high altitude where there is some hope of separating primary CRs from the atmospheric effects. Preliminary experiments (Stroud et al., 1949; Winckler et al. and Stroud 1949) which studied the zenithal and azimuthal dependence and absorbability in lead of the cosmic radiation at about 20 g/cm2 atmospheric depth at 56° N geomagnetic latitude, indicated that although secondary radiation developed particularly at large zenith angles, the bulk of this could be absorbed with lead filters. The primaries and hard secondaries remaining gave an approximately isotropic distribution in zenith and azimuth. One should expect a nearly isotropic distribution of primary flux at this high latitude. Following these preliminary experiments, measurements have been made of the azimuthal asymmetry and latitude effect of the cosmic radiation at various atmospheric depths, but principally between 15 and 25 g/cm2, and at geomagnetic latitudes of 0° , 20° , 30° , and 40° . The experiments were conducted from the USA Norton Sound on a cruise from Port Hueneme, California, to Jarvis Island and back, by arrangement with the ONR and the Chief of Naval Operations. Project "Skyhook" constant-level balloon facilities were provided on the ship by ONR.

The basic measuring instrument was a threefold Geiger counter coincidence telescope consisting of three 10×10 in trays of 1 in diameter counters spaced 50 in between extremes. This construction represented a considerable improvement in the counting rate and angular resolution over the geometry previously employed by Biehl et al. (1948). The advantage of such a large telescope for high-altitude measurements has been demonstrated in Biehl et al. (1948). It is probably relatively less affected by side showers than are small telescopes composed of single counters, and has superior directional properties. The effective or half-angle opening of this telescope was 11° on the side and 16° on the diagonal of the end section. The areasolid angle product was computed from the geometry and, to a sufficiently good approximation, is given by the equation

$$B = \frac{a^2 b^2}{l^2} \left(1 - \frac{a^2 + b^2}{3l^2} \right) \tag{4.67}$$

assuming an isotropic flux of incident particles at high altitude over the aperture of the telescope, and by

$$B = \frac{a^2 b^2}{l^2} \left(1 - \frac{a^2 + b^2}{2l^2} \right),$$
(4.68)

assuming a $\cos^2 \theta$ dependence of the incident particle flux on zenith angle θ at sea level. Here a and b are the tray dimensions and l is the separation. The resolving time as measured by the accidental rate with a radium source nearby, as well as by observation of the pulse in the circuit, was 2µsec. The corrections to the data due to the dead time of the counters and accidentals were negligible. The telescope, complete with high and low voltage dry batteries for 15 h operation, was an independent unit and was mounted on a horizontal shaft through its center of gravity. In most experiments, the bottom counter tray was covered by 10×10 in $\times 3$ cm thick lead plate very close to the counters. This telescope unit was hung by its shaft in a vertical frame (see Fig. 4.128) with a motor and gear drive arranged to control the zenith position during flight. During flight, the entire gondola was rotated at a period of about 18 min by a large gear and motor about a ball-bearing vertical shaft. This shaft was effectively anchored to the balloon by a non-twisting, double suspension about 10 ft below the balloon load ring. The azimuthal bearing was determined by a 3 in nautical compass floating in a 50% water-alcohol mixture in a glass cylinder. A light source in the center of the compass housing and four slits in black paper at 90° intervals around the glass housing covered by type 921 photo-tubes, constituted the sensing device. A 135° sector secured around the outer edge of the compass float with a height sufficient to block the light beam from the photo-tubes registered a new combination of the four photo-tube signals every 45° of azimuth. The readings were checked in the laboratory by rotating the gondola over an azimuth circle, and during flight the absolute direction of the equipment was determined by a photocell recording the sun through a slit. During many of the flights, the zenith angle of the telescope was changed periodically from the vertical to 20° , 40° , or 60° by a control switch on the azimuth gear and a series of positioning switches which also supplied identification signals for the telemetering system. On some flights, the



Fig. 4.128 Complete gondola ready for launching, except for final wrapping (From Winckler et al., 1950)

zenith survey was delayed until the balloon reached its ceiling, and during the rising portion, the telescope was kept at a fixed zenith position. On a number of flights, the zenith mechanism was dispensed with and the telescope secured at a fixed zenith throughout the flight in the interest of better statistical accuracy.

The pressure was measured during the rising portion of the flight by a "Baroswitch" aneroid element, supplemented by a mercury manometer with contacts registering approximately at 8, 10, 12, and 15 mm, which spans the pressure range in which the balloon normally levels off. Temperatures were measured by thermistor elements, and remained in a satisfactory range. The complete gondolas ready to fly weighed from 105 to 115 pounds.

Three telescopes of exactly the same dimension as the gondola units were operated continuously in the vertical position in a light-roofed shelter on the rear deck of the Norton Sound. Figure 4.129 presents all the data taken with the standard telescopes at sea level between 0° and 40° geomagnetic.



Fig. 4.129 Latitude effect observed at sea level. Corrected for barometric effect only (From Winckler et al., 1950)

As can be seen from Fig. 4.129, the total observed effect is 14%, which includes both the temperature and geomagnetic factors. The records of the Carnegie Institution CR Compton-type ionization chambers at Cheltenham and Huancayo were examined over July and August. The only noticeable disturbance was a 2% decrease at both stations on August 4, coinciding with a magnetic disturbance. The intensity steadily increased to normal in about a week. No flights were made on August 3 or 4, and a flight on August 6, failed to show any difference of the vertical intensity at 15 g/cm2 from that of a flight on July 29, both being at $\lambda = 20^{\circ}$.

Graphs of vertical flux versus atmospheric depth at various geomagnetic latitudes are shown in Figs. 4.130 and 4.131. These data were obtained with the 3 cm Pb filter, and are plotted with pressures on a logarithmic scale to accentuate the region of low atmospheric depths. This scale is approximately linear in height above ground. The vertical extension of the plotted points represents the standard statistical deviation, and the width the pressure range over which the data were averaged.

Two flights at $\lambda = 0^{\circ}$ agree quite well (Fig. 4.130). A vertical flux value at ceiling (at 15 g/cm2 atmospheric depth), was obtained without the lead filter, and gives a slightly higher value (0.032 particles/(cm2.sec.ster). At $\lambda = 20^{\circ}$, one complete curve was obtained (Fig. 4.131) with a checkpoint at ceiling from another flight which agrees well. One complete curve was obtained at $\lambda = 30^{\circ}$. One of the three standard telescope units was used for this experiment, having been equipped with telemetering gear and a lead filter in the field (Fig. 4.130). At $\lambda = 40^{\circ}$, one complete curve was measured (Fig. 4.130) with two checkpoints at the ceiling. The full curve does not follow the trend established by the $\lambda = 0^{\circ}$, 20° and 30° curves, and fails to show an increased intensity over the 30° latitude at most atmospheric depths. However, at the ceiling it levels off at a higher flux value than the $\lambda = 30^{\circ}$ curve.

Fig. 4.130 Vertical flux in the atmosphere at various latitudes, with a 3 cm lead filter (From Winckler et al., 1950)



At $\lambda = 40^{\circ}$ there is some scattering of the points at the ceiling, and check values obtained on two other flights at the ceiling height are higher than the full curve. Most of the scattering can be resolved by correcting for the drift of the balloon during flight, or between flights, as the flux increases rapidly with latitude at 40° geomagnetic. There remains at $\lambda = 40^{\circ}$ a difference between a point at the ceiling obtained on flight on July 3, and values on two other flights on August 14 and 15, which is outside the statistical error. Fluctuations in primary intensity may account for some of these irregularities. Figure 4.130 also gives some data obtained in Princeton in November 1948, at $\lambda = 51^{\circ}$ with a small counter telescope of the type used in Stroud



Fig. 4.131 Vertical flux in the atmosphere at $\lambda = 20^{\circ}$, with a 3 cm lead filter (From Winckler et al., 1950)



et al. (1949), and in Winckler et al. (1949). Between 51° N and 56° N no difference in intensity outside experimental uncertainties at low atmospheric depths was detected with these small telescopes. The $\lambda = 51^{\circ}$ flight carried a 1.9 cm Pb filter. At $\lambda = 56^{\circ}$ various thicknesses between 0 and 17 cm Pb were used, and an appropriate value was chosen for comparison with the $\lambda = 51^{\circ}$ data. Since all of the flights reached or approached the 15 g/cm2 level, the latitude effect can be studied at this depth with little or no extrapolation. The eight measurements of the experiment of Winckler et al. (1950), which constitute a self-consistent set, all made with identical apparatus, are plotted logarithmically in Fig. 4.132.

A straight line drawn through the experimental points in Fig. 4.132 can be represented by the equation

$$I(>E) = 0.30E^{-0.90\pm0.05} \tag{4.69}$$

and is the integral number-energy spectrum for primaries. The differential numberenergy spectrum derived from this, i.e., the flux of particles in unit energy interval at E, is

$$D(E) = 0.27E^{-1.90\pm0.05}.$$
(4.70)

The azimuthal effect was studied as a function of atmospheric depth by collecting the data in three 45° western and eastern sectors. The result of averaging the telescope counting rate over 135° of azimuth in each direction was to decrease the observed east-west asymmetry, but was necessitated by the short time spent by the balloon in each pressure interval during the ascent of the flight. Intervals of 10 min were used during most of the ascent, but were increased in length near the ceiling as the balloon leveled off, and the lowest pressure points include all of the ceiling data averaged together. In this type of analysis, no reference was made to the azimuthal standardization, and the two 135° sectors represent the eastern and western directions only to within 15° or 20°. In one or two of the intervals during ascent, the balloon rotated so rapidly that the inertia of the compass produced considerable overshooting and lagging in the azimuthal indications. This effect was discovered by correlating the sun reference photocell with the compass, and it was noticed that during such intervals the east-west values fluctuated beyond the statistical error, and usually the east-west asymmetry was reduced. Fortunately, these intervals were not numerous enough to appreciably influence the average curve. Figures 4.133 and 4.134 give the east-west effect as a function of depth for $\lambda = 0^{\circ}$ and $\lambda = 40^{\circ}$, for 60° and 40° zenith angles.

Figures 4.135, 4.136, and 4.137 give similar curves at $\lambda = 20^{\circ}$ for 20° , 40° , and 60° zenith angles, respectively.

The curves in Figs. 4.133–4.137 show that the east–west effect increases with decreasing depth, and does so with increasing rapidity between 300 and 100 g/cm2. The east–west effect is larger at $\lambda = 0^{\circ}$ than at $\lambda = 40^{\circ}$, as would be expected from geomagnetic considerations, and apparently at $\lambda = 0^{\circ}$ persists relatively further into the atmosphere than at $\lambda = 40^{\circ}$. Both the easterly and westerly curves pass through a mild maximum between 50 and 100 g/cm2.

Above this, at $\lambda = 0^{\circ}$ a leveling-off process seems to take place, but at $\lambda = 40^{\circ}$ a sharp downward trend persists to the highest altitudes reached. It was hoped that such data would permit the trend of the asymmetry to be mapped out as a function of depth near the top of the atmosphere as an aid in estimating the effect of the atmosphere on the measurements. However, if the asymmetry is plotted as a function of depth in this region no consistent picture emerges. In some cases the asymmetry remains constant, and in others it increases or decreases. It is probable that the statistical accuracy during the ascending portion of the flights is not sufficient to give detailed information of this sort. Of more interest is the curve in Fig. 4.138, at zenith angles 0° and 40° , without the 3 cm Pb filter.



Fig. 4.133 The Eastern and western rates as a function of atmospheric depth at a 60° zenith angle. Data summed in 135° azimuthal sectors. Upper gondola at August 15, 1949 ($\lambda = 40^{\circ}$), lower gondola at July 21, 1949 ($\lambda = 0^{\circ}$) (From Winckler et al., 1950)

From Fig. 4.138 it can be seen that the large maxima occur in both the east and west portions, and the asymmetry, or at least the east–est difference, is preserved to a surprising degree. For comparison, the corresponding curve with the 3 cm Pb filter is shown. The asymmetry without the filter is only a little smaller at various depths than with it, a result that is in agreement with the measurements made by Biehl et al. (1949) at 250 to 300 g/cm2 atmospheric depth. The asymmetry at the top of the atmosphere, and with the data summed in 45° azimuthal sectors, increases to 50% without lead, and 54% with 3 cm Pb (see Table 4.17).

According to Winckler et al. (1950), the described investigation yields two principal results. The first of these, the number-energy spectrum of primary CRs is obtained from the vertical flux measurements at various latitudes. The success of



Fig. 4.134 Eastern and western rates in 135° sectors of azimuth at 40° zenith angle. Upper gondola at July 3, 1949 ($\lambda = 40^{\circ}$), lower gondola at July 19, 1949 ($\lambda = 0^{\circ}$) (From Winckler et al., 1950)



Fig. 4.135 Eastern and western rates at $\lambda = 20^{\circ}$, zenith angle 20°. Gondola at July 28, 1949 (From Winckler et al., 1950)



Fig. 4.137 Eastern and western rates at $\lambda = 20^{\circ}$, zenith angle 60°. Gondola at July 27, 1949 (From Winckler et al., 1950)

these measurements depends on how completely the flux of ionizing particles at about 15 g/cm2 matches, in number and direction, the primary flux. The assumption is made that the measured ionizing particles capable of penetrating 3 cm of Pb are largely primaries, and that the remainder of events are proportional to the primary flux. The various measurements can then be satisfactorily represented by the

Fig. 4.138 Eastern and western rates at $\lambda = 0^{\circ}$, zenith angle 40° without the customary 3 cm Pb filter. Lower curves – same measurements with filter (From Winckler et al., 1950)



Table 4.17 Observed and predicted azimuthal asymmetry $A = 2(I_W - I_E)/(I_W + I_E)$

Geomagnetic	Zenith angle	Shielding	Azimuthal asymmetry			
latitude			Predicted	Observed		
0°	40°	No Pb	0.81	0.50 ± 0.08		
	60°	No Pb	1.20	0.50 ± 0.09		
	40°	3 cm Pb	0.81	0.54 ± 0.10		
	60°	3 cm Pb	1.20	$0.\pm0.05$		
20°	20°	3 cm Pb	0.41	$0.\pm0.10$		
	40°	3 cm Pb	0.71	0.48 ± 0.06		
	60°	3 cm Pb	1.08	0.58 ± 0.05		
40°	40°	3 cm Pb	0.31	0.24 ± 0.09		
	60°	3 cm Pb	1.02	0.26 ± 0.07		

differential number-energy spectrum described by Eq. 4.69. If the flux at 15 g/cm² has a constant proportionality to the true primary flux at various energies, then the exponent γ is correct.

The second principal result is obtained by comparing the east-west asymmetry and latitude effects over the same energy ranges. This can be done independently of the nature of the particles by using Störmer's units of energy. In nearly every case the east–west effect is smaller than the latitude effect. It was suggested that scattering or/and production of particles upward from below the measuring instrument may account for the differences, and that this effect should be investigated before negative primaries are assumed. It would be desirable to increase the statistical accuracy of the experiments, but it seems obvious that the possible atmospheric influences are considerably larger than the purely statistical errors. It is regrettable that none of the equipment was recovered for post-flight checks, but a number of other methods following the behavior of the apparatus, indicated that the data presented in Winckler et al. (1950) have satisfactory reliability. Although the design of the measuring telescope is such as to reduce the effects of air showers and locally produced bursts.

Chapter 5 Main Results of Cosmic Ray Survey to Antarctica on the Ship *Italica* in 1996/97

5.1 Description of Apparatus, Trajectory Calculations of Cutoff Rigidities in the Real Geomagnetic Field Along the Ship's Voyage

5.1.1 Importance of Obtaining Exact Data in CR Latitude Surveys

Together with direct measurements of primary CR, either with space probes outside the geomagnetic field or with balloons in the upper atmospheric layers, the technique of continuous measurements of the secondary components by groundbased detectors is a unique source of information on the temporal variations of the CR distribution function external to the magnetosphere, as well as the cutoff rigidity planetary distribution. These variations contain important information on the dynamic processes in the Heliosphere and acceleration phenomena in the solar atmosphere; their study is an essential tool for determining the models appropriate to different modulation processes. A "great instrument" consisting of the geomagnetic field, the earth's atmosphere, and all the CR detectors located on the earth's surface provides a continuous monitoring of primary variations in a wide rigidity interval and for all directions of incoming particles out of the magnetosphere. The global-spectrographic method (Dorman, M1974; Belov et al., 1983) based on the knowledge of coupling functions (Dorman, M1957) furnishes an efficient mathematical tool for this purpose. The core of the "great instrument" is the worldwide network of CR neutron monitors, which are sensitive to temporal variations of primaries with rigidities up to \sim 40 GV. The technique of latitude surveys of the CR nucleonic component is the most reliable method of calibrating the "CR geomagnetic spectrometer" and for determining the coupling functions needed for studying temporal variations of the primary CR spectrum using data from the neutron monitor station network (see the reviews in Dorman, M1974, M1975, M2004; also see Bachelet et al., 1965,1972, 1973; Dorman et al., 1966, 1967a, b, c; Lockwood and Webber, 1967; Kodama, 1968; Keith et al., 1968; Carmichael and Bercovitch, 1969; Allkofer et al., 1969; Alexanyan et al., 1979a, b, 1985; Potgieter et al., 1980a, b; Moraal et al., 1989; Nagashima et al., 1989; Stoker, 1993; Stoker and Moraal, 1995; Bieber et al., 1997; Villoresi et al., 1997, 1999). Moreover, with latitude surveys it is also possible to control the evaluation of geomagnetic cutoff rigidities and detect geomagnetic anomalies (see Stoker, 1995; Stoker et al., 1997; Clem et al., 1997). However, to obtain reliable latitudinal variations in the CR nucleonic component, it is necessary to apply refined analysis techniques to the raw data recorded along the survey. Papers by Villoresi et al. (1999, 2000), Iucci et al. (1999, 2000), and Dorman et al. (1999, 2000) describe the latitude survey experiment performed with neutron detectors on board the ship *Italica* during 1996/97, as part of the Italian Antarctic Research Program. An entire complex procedure was developed which we applied to produce valid reduced data and accurate determination of the coupling functions.

5.1.2 Principles of the Data Corrections Method

The method used is principally based on a thorough evaluation of several meteorological and geomagnetic effects. Corrections for meteorological effects, to be considered when dealing with neutron monitor latitude surveys on seas, should include:

- 1. Determination of the atmospheric-absorbing mass, by taking into account the effect of wind (Bernouilli effect) on barometric data, as well as the variation of gravitational acceleration g with geographic position
- 2. Determination of atmospheric absorption coefficients appropriate to the current solar-cycle phase and their variability with cutoff rigidity
- 3. Evaluation of intensity changes due to latitudinal and temporal variations in the temperature distribution of the atmospheric column
- 4. Estimate of intensity variations due to the tilt effect of the neutron monitor (seastate effect)

Interplanetary and geomagnetic effects to be considered are:

- 1. Correction for isotropic temporal fluctuations in the primary CR
- 2. Correction for CR north-south asymmetry in the interplanetary space
- 3. Determination of cutoff rigidities for a vertical particle incidence by taking into account the penumbra effect, and of apparent cutoff rigidities by taking into account the contribution of nonvertical incidence
- 4. Correction for temporal variations of the CR east-west effect caused by the asymmetric shielding mass around the neutron detectors

The survey itself offers a unique opportunity for accurate determination of several of the afore-mentioned effects. Meteorological and geomagnetic effects were treated in detail in Iucci et al. (1999, 2000), and Dorman et al. (1999b, 2000). For some of these computations and corrections we applied standard techniques. Some of them have been improved (e.g., sea-state effect) and others, as far as we know, have never been considered before in the analysis of neutron monitor survey data (e.g., the effect of wind on the determination of atmospheric absorbing mass, north– south anisotropy, and east–west geomagnetic effect). In this section we describe the experiment and the general procedure adopted for data processing, including several analyses for data quality assurance, and correct the data for interplanetary variations in CR flux and for all meteorological effects, on the basis of results obtained by Iucci et al. (2000). In a final test, the validity of the experiment and applied procedures is evaluated by estimating the residual fluctuations of "fully corrected" data. We used threshold rigidities computed in Dorman et al. (2000, 2001, 2003), in which geomagnetic effects are investigated and coupling functions are determined and compared with previous results.

5.1.3 Description of the Experiment

The instrumentation was installed inside an air-conditioned container capable of maintaining relative humidity below 55% and temperature between 18° and 25°C along the survey. The high-energy CR nucleonic component intensity was measured with a standard 3NM-IQSY super neutron monitor (counters N1, N2, N3). The thickness of the lateral polyethylene slabs was increased from the usual 7 cm to 14 cm to achieve better shielding of the detector from neutrons produced by CR interactions with surrounding matter. Over the 3NM-IQSY, on the extreme left and right sides, two additional BF3 counters without lead and polyethylene (bare counters Bl, B2) were used for recording the background flux of thermalized neutrons (see Fig. A5.1).

The low-energy neutron component detected by two bar counters can provide information on locally produced thermalized neutrons, whose flux can be significantly influenced by changes in the distribution and composition of environmental matter, and by local radioactive elements in soil, rocks, and the atmosphere.

5.1.4 The Recorded Data and Acquisition System

The following data were recorded at 5-min intervals using a standard data acquisition system:

- 1. Geographic position and universal time provided by a Global Position System (GPS)
- 2. Atmospheric pressure by a high-precision device utilizing a vibrating cylinder transducer (resolution 0.01 mbar, precision 0.1 mbar, stability 0.1 mbar per year); an additional pressure sensor (0.2 mbar resolution) was also operating
- 3. Internal temperature and relative humidity and external temperature
- 4. The values of high and low voltages
- 5. The integral 5-min value of CR intensities measured by each counter (I_{N1} , I_{N2} , I_{N3} of 3NM and I_{B1} , I_{B2} of bare counters)
- 6. Speed and direction of winds (provided by a companion experiment)

The 5-min data have been used only for checking data quality. For each individual counter, the statistical consistency of the intensity fluctuations was controlled on a 5-min timescale. The complete data analysis was mainly based on 3-hourly averages. Information on sea-state strength was obtained twice daily from the ship's records; 3-hourly values were computed by linear interpolation.

5.1.5 Quality Assurance Procedures: Presurvey and Postsurvey Measurements

The response of the 3NM-IQSY and the 2BC (bare counters) neutron detectors and associated devices used in the latitude survey was monitored for 7 days (November 25 through December 1, 1996) before and 7 days (April 11-17, 1997) after the survey. The detectors operated inside the container in an industrial area, located ~80km southeast of Rome near the village of Colli ($\lambda = 41.67^{\circ}$ N, $\varphi = 13.52^{\circ}$ E, 230 m above sea level), where the instrumentation was assembled. In particular, the overall counter stability was controlled through multichannel pulse distribution tests (this was also done periodically during the survey). The comparison between the calibrations of barometric pressure devices taken before and after the survey did not show any appreciable long-term change. CR records of monitors operating in Colli have been compared with the contemporary data of the Rome 17NM-IQSY detector (cutoff rigidity 6.2 GV, $\lambda = 41.91^{\circ}$ N, $\varphi = 12.50^{\circ}$ E). Prior to that, an internal analysis of the five independent sections of the Rome 17NM-IQSY demonstrated that the efficiency of this detector did not change during the survey period. Then, simultaneous pressure coefficients before and after the survey were computed. The barometric pressure P in hectopascals was transformed to the mass M (in g cm⁻²) of the air vertical column, by taking into account the changes with latitude λ and longitude φ of gravitational acceleration according to Uotila (1957) (for more details, see Chapter 16 of Dorman, M2004). We performed a linear correlation between the 3-hourly values of the logarithm of the CR intensity I and the mass of the vertical air column M: $\ln(I) = \beta M + b$. The values of the atmospheric absorption coefficients β and of the corresponding correlation coefficients *R* are given in Table 5.1.

•					
CR detector	Rome, 17NM	Colli, 3NM	Colli, 2BC		
	Before CR la	titude survey			
$-\beta(\% g^{-1} cm^{-2})$	0.661 ± 0.008	0.665 ± 0.010	0.613 ± 0.021		
Correl. coef. (R)	-0.9958 ± 0.0007	-0.9944 ± 0.0010	-1.971 ± 0.005		
	After CR lat	itude survey			
$\beta(\% g^{-1} cm^{-2})$	0.690 ± 0.013	0.694 ± 0.019	0.610 ± 0.040		
Correl. coef. (R)	-0.9909 + 0.0016	-0.9806 ± 0.0034	-0.904 ± 0.016		

 Table 5.1 Atmospheric absorption coefficients measured in Rome and Colli before and after the survey (According to Villoresi et al., 2000)

As seen from Table 5.1, absorption coefficients for the NM operating in Colli and for the Rome 17NM-IOSY are equal within the limits of error. They are consistent with the value expected for the 3NM-IOSY operating, during the solar minimum, at 6.2 GV rigidity threshold near sea level (e.g., Bachelet et al., 1972). For both monitors, the computed β values slightly increased from November 1996 to April 1997. Absorption coefficients for the 2BC detector are significantly smaller than for the NM-IOSY. We notice that a ground-based 2BC is also sensitive to thermalized low-energy neutrons generated in nearby matter and to local radioactive materials. Since this contribution to the counting rate is mostly independent of M variations, the atmospheric absorption coefficient for the 2BC is expected to be smaller than for the NM-IQSY. Moreover, the lower value of the correlation coefficient for the 2BC detector cannot be fully attributed to the reduced counting rate; in fact, since the 2BC is particularly sensitive to changes in the atomic composition of nearby matter (see Section 5.1.7), additional noise in 2BC counting rate will be present. The efficiencies of the 3NM-IQSY and the 2BC detectors before and after the survey have been checked by the ratio between data measured in Colli and in Rome (17NM-IQSY). Comparison was done on 3-hourly pressure-corrected data because of different pressure variations in the two sites due to the 80 km relative distance and to the difference in altitude. The temporal behavior of the Colli/Rome ratio is shown in Fig. 5.1.



Fig. 5.1 Comparison between 3-hourly pressure-corrected neutron intensities measured by the Rome 17NM-IQSY and survey detectors (3NM-IQSY and 2BC) in Colli, before (thick line, November 25 through December 1, 1996) and after (thin line, April 11–17, 1997) survey: a 3NM-IQSY/17NM-IQSY; b 2BC/17NM-IQSY. The two-sigma intervals are shown (According to Villoresi et al., 2000)

For the 3NM-IQSY, this ratio shows a small change at the limit of statistical fluctuations, the average values being 0.18336 ± 0.00014 before the survey and 0.18385 ± 0.00015 after the survey, indicating that the 3NM-IQSY efficiency remains stable within 0.3% during the survey time. For the 2BC, we obtain 0.017345 ± 0.000034 before the survey and 0.016814 ± 0.000030 after the survey. The possible 3% decrease in the counting rate of the 2BC detector could be caused by nearby changes in distribution of matter in Colli (for the 3NM, small environmental changes are not important).

5.1.6 The Latitude Survey: Route and Main Results

On December 19, 1996, the container was moved to the port of Ravenna (300 km north of Rome on the Adriatic Sea) and was installed on the upper deck of the ship *Italica* to minimize the CR shielding effects. Sternward, the zenith angle $45-90^{\circ}$ was partially shielded by the upper structure of the ship, as schematically shown in Fig. 5.2. On December 21, the ship sailed from Ravenna to Antarctica. The Italian Antarctic Base "Baia Terra Nova" (BTN) was reached on February 2, 1997. On March 26, 1997, the ship returned to Ravenna following the same route (see Figs. 5.3 and 5.4). We note that along the survey route we attained almost the highest rigidity thresholds available on the earth. The experiment was continuously running; only for three days (February 26–28, 1997) was the data acquisition halted during an exceptional sea storm, during which the computer keyboard was damaged by water leakage from one of the air conditioners. Two days later, it was possible to access the container and repair the damage.

Table A5.1 lists the most relevant survey data on a daily basis: normalized intensities of the 3NM-IQSY and 2BC detectors (the average counting rate at



Fig. 5.2 Schematic view of the container relative to the shielding structure on the ship



Fig. 5.3 The route of the latitude survey drawn on a portion of the map of the globe



Fig. 5.4 The route of the latitude survey 1996/97 drawn on a cutoff rigidity contour map trajectory numerically calculated by Smart and Shea (1995)

 $R_{\rm cp} \leq 1.0 \,{\rm GV}$ and $M_o = 1,034 \,{\rm gcm}^{-2}$ was 9,182.1 count.(5 min)⁻¹ for the 3NM-IQSY and 838.8 count.(5 min)⁻¹ for the 2BC) corrected for interplanetary and meteorological effects together with the atmospheric pressure *P*, the average daily geographic coordinates, and the vertical cutoff rigidity $R_{\rm cp}$ corrected for the penumbra effect $\Delta R_{\rm cp}$ (details on the computation of $R_{\rm cp}$ and $\Delta R_{\rm cp}$ are given in Section 5.3).

The pole ($R_{cp} \le 1 \text{ GV}$) to equator ($R_{cp} = l6.5 \text{ GV}$) neutron intensity variation is found to be 2.00 for 3NM-IQSY and 2.25 for 2BC. This difference between the two detectors is essentially due to CR primaries at low rigidity (<5 GV).

5.1.7 The Quality Assurance Procedures and Internal Tests

Intensity ratios $r_1 = I_{N1}/(I_{N1} + I_{N2} + I_{N3})$, $r_2 = I_{N2}/(I_{N1} + I_{N2} + I_{N3})$, $r_3 = I_{N3}/(I_{N1} + I_{N2} + I_{N3})$, I_{B1}/I_{B2} , $I_{2BC}/I_{3NM} = (I_{B1} + I_{B2})/(I_{N1} + I_{N2} + I_{N3})$ are shown in Fig. 5.5.



Fig. 5.5 The comparative long-term behavior of 3-hourly data as recorded by different counters and detectors during the whole survey (According to Villoresi et al., 2000)

From Fig. 5.5 it can be seen that the central counter N2 of the 3NM-IQSY detector has the highest counting rate, as expected. Ratios r_1 and r_3 show small systematic variations associated with cutoff rigidity, indicating differences of about 1% in the overall latitude effect of individual NM-IQSY counters. Variations in shielding, electronic dead time, and a particle contamination could be responsible for the small effect. The ratio I_{B1}/I_{B2} is about 5% higher in equatorial regions where the particle production in shielding matter becomes relatively more important.

The behavior of the ratio I_{2BC}/I_{3NM} indicates that the overall latitude effect of the BC is about 10% larger than for the NM-IQSY, since bare counters are more sensitive to lower energies. Moreover, changes in the surrounding masses and increases in local radioactivity, occurring when the ship was in ports or in their proximity, produce large increases in the I_{2BC}/I_{3NM} ratio. Increases in the average atomic number of nearby masses and in local radioactivity will increase the flux of atmospheric thermalized neutrons counted by the BC. This "port effect" is not observed for the NM-IQSY (because the most of the counting rate is due to neutron interactions in lead inside the detector). Data from the 2BC detector recorded in or near ports have been eliminated from the analysis.

5.2 Correction for Primary CR Variations and Summary of All Corrections

5.2.1 Primary Isotropic Time Variations

Latitude survey data have to be corrected for primary time variations which occurred during the survey; that is, normalized to a specific primary condition. The entire survey occurred during the solar minimum and is characterized by very small CR time variations, as can be seen in Fig. 5.6, where we show the neutron monitor intensity recorded by the Rome 17NM-IQSY detector.

To optimize the correction for primary variations occurring during the survey, we used the synoptic changes shown by the network of sea-level stations (about 20 NM-IQSY detectors), by choosing the average intensity during the complete survey time as a reference level. A correction factor has been computed for each day by interpolation between stations having R_{cp} values as close as possible (at least one lower and one higher) to the R_{cp} value of the ship for that day. The correction has been applied on daily values to avoid bias produced by diurnal anisotropy. Therefore residual changes due to short-term fluctuations and diurnal variations (see Fig. 5.6) are present in the 3-hourly data; their effect is expected to be larger at low rigidity thresholds.



Fig. 5.6 The neutron intensity, in percent variations relative to the average intensity of the survey period, as recorded by the Rome 17NM-IQSY during the latitude survey. The heavy line at the bottom of each panel marks the period covered by the survey (According to Villoresi et al., 2000)

5.2.2 Corrections for Primary North–South Asymmetry of CR Distribution in the Interplanetary Space

CR latitude survey data are influenced by the small north–south asymmetry of the CR distribution in the interplanetary space. This asymmetry was investigated using the data from the worldwide network of high-latitude CR stations in the northern and southern hemispheres (Belov et al., 1987, 1990). It was found that the amplitude of the CR north–south asymmetry in the NM intensity is $A_{\rm NS} \leq 1\% (A_{\rm NS} > 0 \text{ when } I_{\rm N} > I_{\rm S}$ and $A_{\rm NS} < 0$ when $I_{\rm N} < I_{\rm S}$). The relative CR intensity distribution on the earth caused by the north–south asymmetry with amplitude $A_{\rm NS}(t)$ can be described as

$$\frac{\Delta I(\lambda, t)}{I_o} = A_{\rm NS}(t) \sin \lambda, \qquad (5.1)$$

where

$$A_{\rm NS}(t) = \frac{I(+90^{\circ}, t) - I(-90^{\circ}, t)}{I(+90^{\circ}, t) + I(-90^{\circ}, t)}.$$
(5.2)

In Eq. 5.1 λ is the geographic latitude ($\lambda > 0$ in the northern hemisphere and $\lambda < 0$ in the southern hemisphere) and $I(\lambda,t)$ is the CR intensity recorded at time t by a NM station at latitude λ . A recent investigation by Belov et al. (1995) showed that the CR north–south asymmetry $A_{NS}(t)$ has a seasonal variation with a maximum + 0.5% in May–August and a minimum – 0.5% in December–March. We used

these results for our survey data, assuming the same seasonal variation of $A_{\rm NS}(t)$ for 1996/97 as observed by Belov et al. (1995). During the period of the latitude survey (December 1996–March 1997), the expected CR intensity variation has been computed by Eq. 5.1 and used for the data correction (see Fig. 5.7).



Fig. 5.7 Summary of meteorological effects on 3NM-IQSY intensity and atmospheric mass, together with the effect of CR isotropic primary variations and north–south asymmetry and the variation of R_{cp} and gravity acceleration g during the survey. From top to bottom: cutoff rigidity R_{cp} and g (in the same panel); atmospheric absorption coefficient β , atmospheric mass M, wind effect on atmospheric mass fM_b , the effect of atmospheric mass ($M + fM_b$) changes on counting rate; the sea-state effect on the NM-IQSY counting rate (for 2BC the effect is two times larger); the effect of CR isotropic primary variations; the effect of CR north–south asymmetry; and the effect of atmospheric temperature changes on the 3NM-IQSY counting rate (According to Villoresi et al., 2000)

5.2.3 The Summing of all Corrections Including Meteorological Effects

To the set of 3-hourly data corrected for changes in the CR flux around the earth (isotropic time variations as was described in Section 5.2.1 and north–south asymmetry as was described in Section 5.2.2), we applied the corrections for meteorological effects which were described in details in Chapter 16 of Dorman (M2004). We emphasize that these results have a crucial relevance to the analysis here, because they describe the experimental and theoretical approaches utilized for the determination of meteorological effects. These effects include: (1) changes in the absorbing atmospheric mass, as determined by barometric data, by taking into account the change of barometric coefficient with cutoff rigidity R_{cp} as well as wind effect and the local value of gravitational acceleration g; (2) changes produced by ship oscillations (sea-state effect); and (3) changes in the temperature distribution in the atmospheric column.

Figure 5.7 shows the individual contributions of each effect on data correction during the survey period. Results given in Fig. 5.7 indicate that all these effects should be taken into account, since the amplitude of each correction is much greater than the statistical limits of the data:

- 1. Up to 40% for changes in atmospheric absorbing mass (including $\sim 3\%$ effect for Antarctica-to-equator change in g and up to 1.3% for the wind effect)
- 2. Up to about 1.2% in the case of the 3NM (2.5% in the case of the 2BC) for the sea-state effect
- 3. One percent for Antarctica-to-equator change in atmospheric temperatures; and
- 4. Up to 1% for north–south anisotropy.

Moreover, we note that the biggest meteorological corrections take place in the Antarctic region. Data corrected for all these effects will be used in Sections 5.3 and 5.4.

5.2.4 Quality Assurance Procedure: Internal Comparison of Corrected Data

On the basis of computations given by Dorman et al. (2000) and described below, in Section 5.4, we attributed an average vertical threshold rigidity to each 3-hourly geographic position. We computed normalized 3-hourly intensity data $I_{3NM}(R_{cp})$ and $I_{2BC}(R_{cp})$ as well as

$$J_{3NM}(R_{cp}) = I_{3NM}(R_{cp})/I_{3NM}(<1\,\text{GV}), J_{2BC}(R_{cp}) = I_{2BC}(R_{cp})/I_{2BC}(<1\,\text{GV}),$$
(5.3)

where I_{3NM} (<1 GV) and I_{2BC} (<1 GV) are the intensities at R_{cp} < 1 GV. According to measurements in the Antarctic region, we found that

5.2 Correction for Primary CR Variations and Summary of All Corrections

$$I_{3NM} (< 1 \,\text{GV}) = 330,556 \,\text{counts} \times (3 \,\text{hours})^{-1}$$
 (5.4)

for the 3NM-IQSY detector, and

$$I_{2BC} (< 1 \,\text{GV}) = 30,160 \,\text{counts} \times (3 \,\text{hours})^{-1}$$
 (5.5)

for the 2BC detector.

The quality of the CR survey data can be evaluated by the amplitude of the fluctuations about the average behavior. For the northern and southern hemispheres and for different rigidity intervals, we estimated the standard deviation s.d._{obs} of 3-hourly values, by computing the s.d. of

$$\left(\Delta J/J\right)_{i} = 1 - (J_{i+1} + J_{i-1})/2J_{i}, \tag{5.6}$$

where J_i , is the *i*-th 3-hourly normalized intensity value in the cutoff rigidity sequence of data determined by Eq. 5.3. We computed the quantity

$$\chi = \text{s.d.}_{\text{obs}/\text{s.d.}_{\text{exp}}},\tag{5.7}$$

where s.d._{exp} is the standard deviation expected on the basis of counting rate. At $R_{cp} > 6$ GV, we found $\chi = 1.1$ for the 3NM-IQSY detector and $\chi = 1.3$ for the 2BC detector (e.g., at $R_{cp} = 13$ GV, for the 3NM-IQSY detector s.d._{obs} = 0.35% and s.d._{exp} = 0.31%; for the 2BC detector s.d._{obs} = 0.9% and s.d._{exp} = 0.7%). At $R_{cp} < 4$ GV, we found $\chi = 1.6$ for the 3NM-IQSY detector and $\chi = 1.9$ for the 2BC detector. This small increase in fluctuations at lower cutoff rigidities can be attributed to small residual effects: (1) insufficient corrections for CR primary variations due to the lack of NM-IQSY station data in the southern hemisphere and to the use of daily values for corrections (see Fig. 5.6); and (2) insufficient corrections at high latitudes (see Fig. 5.7).

Moreover, the CR east–west asymmetry along forward (from Italy to Antarctica) and backward (from Antarctica to Italy) routes can contribute to increasing the fluctuations, especially for the 2BC detector (forward–backward effect). This small forward–backward effect could be caused by the 180° rotation with the ship of the asymmetric distribution of matter around the detectors (see Fig. 5.2), relative to the asymmetric distribution of cutoff rigidities (the so-called east–west effect) and will be discussed in Section 5.4. For the 3NM-IQSY detector, the effect appears to be very small, where only in the northern hemisphere for $R_{cp} = 9-11$ GV is a systematic difference of ~1% observed, while for the 2BC detector, the effect has a larger amplitude (~3%) and covers a wider rigidity interval (9–15 GV).

We also estimated the standard deviation for short-term variations s.d._{st}, by computing the s.d. of $(\Delta J/J)_i$ determined by Eq. 5.6. In this case, the contribution of the forward–backward effect disappears and insufficiency in corrections for meteorological effects and CR primary variations is reduced. For $R_{cp} > 6$ GV, the ratio s.d._{obs/}s.d._{exp} = 1.05 for both detectors, and for $R_{cp} < 4$ GV, s.d._{obs/}s.d._{exp} = 1.4. Furthermore, we analyzed the latitudinal intensity curves recorded by individual counters to check the consistency of each counter's intensity and to avoid the possibility of some instrumental contribution to the previously mentioned small discrepancies. The 3-hourly counting rates of individual counters have been corrected by the same procedure used for the total 3NM-IQSY and 2BC data, obtaining the same small effects observed for the whole detectors. As already discussed in Section 5.1.7, the only remarkable disagreement among individual NM counters is observed in the magnitude of pole-to-equator intensity ratios (less than $\sim 1\%$, see Fig. 5.4).

5.2.5 Critical Consideration of Results in Sections 5.1 and 5.2.1– 5.2.4

In these Sections we presented the design and operation of the latitude survey experiment conducted on board the ship Italica of the Italian Antarctic Research Program (PNRA) during the austral summer 1996/97. Two neutron detectors, a standard 3NM-IQSY and a 2-bare-counter detector (2BC) were in operation on the ship. The analysis of data recorded before, during, and after the survey showed that the data quality was sufficiently accurate to assure the determination of reliable coupling functions of neutron monitor intensity for the 1996/97 solar minimum. The comparison between simultaneous data from the 3NM-IQSY detector and from the 17NM-IQSY of the Rome station before and after the survey showed that the efficiency of the 3NM-IQSY remained stable within 0.3%; this comparison also showed that the 3NM-IQSY detector on the ship Italica responds to atmospheric mass changes like the standard 17NM-IQSY in Rome. Moreover, stability in the efficiency of the 3NM-IQSY was assured by the behavior of the ratios among different counters during all the survey period; the fluctuations of these ratios, about a slowly changing rigidity-dependent variation, are consistent within statistical limits. In these Sections we utilized the cutoff rigidities computed by Dorman et al. (2000) for vertically incident CR particles along the survey route, by taking into account the penumbra effect. The low-energy 2BC detector exhibits an $\sim 10\%$ larger latitude effect as compared to the 3NM-IQSY high-energy detector, because of the larger contribution of galactic CR particles with rigidity lower than 5 GV to the BC counting rate. Moreover, single counters of the 3NM-IOSY show slightly different (<1%) overall latitude effects. This is not surprising, since the energy response of individual BF₃ counters of 3NM-IQSY depends on a number of factors such as position, shielding effects, electronic dead time, and a particle contamination of the counter's walls. Since these small differences are most likely to be present in every neutron monitor, our 3NM-IQSY detector could be considered as being a typical station of the worldwide network. For the first time, a complete correction for meteorological and interplanetary effects has been applied to survey data. A detailed evaluation of meteorological effects was given by Iucci et al. (2000) and was considered in details in Chapter 16 of Dorman (M2004). We compared the corrected 3-hourly NM data as recorded in the same position and at the same cutoff in forward and reverse trips. The stability of the experiment and the appropriate corrections for the aforementioned effects have been demonstrated by the computed standard deviations of the data. For both the 3NM and the 2BC detectors, the only remarkable increase in fluctuations took place at $R_{cp} < 4$ GV; we point out that in this area the variations, due to meteorological effects, are particularly large and the correction for primary variations cannot be fully applied, especially to 3-hourly data. The most relevant test on the fully corrected NM data showed that in the comparison of data taken in the same place at significantly distant times, the standard deviation s.d._{obs} of each 3-hourly value is (0.34–0.38%) all along the survey. This small value of s.d._{obs}, in comparison with the overall corrections applied for each effect, demonstrates the reliability of the method and the necessity of taking into account all the effects considered in this set of papers, when dealing with latitude survey data in ocean areas.

5.3 Computation of Cutoff Rigidities of Vertically Incident CR Particles for Latitude Survey

Cutoff rigidities of vertically incident CR particles have been calculated using a numerical trajectory method (McCracken et al., M1962; see also in Chapter 3) for each day for the corresponding average geographic location of the ship. Computations were done by considering the earth's total magnetic field as the sum of fields generated by both internal and external sources. The main geomagnetic field from internal sources is represented by a Gaussian series with the International Geomagnetic Reference Field 1995 coefficients (IAGA Division V, Working Group 8, 1996) up to n = 10, extrapolated to the epoch of the survey. Note that the secular variation of the main geomagnetic field is too small to affect the results of calculations during the survey time. The magnetic field from external sources is represented by the magnetospheric magnetic field model developed by Tsyganenko (1989). It takes into account the contribution from (1) ring current, (2) the magnetotail current system including the plasma sheet current and return currents, and (3) magnetopause currents as well as the large-scale system of field-aligned currents. Calculations were done for a quiet magnetosphere ($K_p = 0$), corresponding to the "quiet" solarinterplanetary conditions observed during the survey period. For each point, we computed the upper cutoff rigidity R_c , which is the rigidity value of the highest detected allowed/forbidden transition among the computed trajectories (e.g., Cooke et al., 1991), and the lowest cutoff value R_L , which is the rigidity value of the lowest allowed/forbidden transition. Calculations have been done for 0.001 GV steps. The effective cutoff rigidity R_{cp} is defined by the condition

$$\sum_{R_j=R_{\rm cp}}^{R_{\rm c}} W_j \Delta R_j = \sum_{R_j=R_{\rm L}}^{R_{\rm c}} W_j \Delta R_j \,(\text{allowed}), \tag{5.8}$$

where W_j is the coupling function in the ΔR_j interval. Under the reasonable hypothesis of a flat W(R) in the $R_L - R_c$ interval (flat CR spectrum approximation, e.g., Shea et al., M1976), we obtain



$$R_{\rm cp} = R_{\rm c} - \Delta R_{\rm cp} = R_{\rm c} - \sum_{R_j = R_{\rm L}}^{R_{\rm c}} \Delta R_j \,(\text{allowed}). \tag{5.9}$$

We used $\Delta R_j = 0.01 \text{ GV}$ intervals for this calculation. Results obtained for each daily average geographic location of the ship along the latitudinal survey were presented in Table A5.1 (see Section 5.1.6).

In Fig. 5.8, we plot ΔR_{cp} as a function of R_{cp} . For our survey it appears that the ΔR_{cp} correction is more relevant (up to $\sim 1 \text{ GV}$) in the northern hemisphere in the $\sim 8-13 \text{ GV}$ interval. From the R_{cp} daily values, we determined the R_{cp} values for each 3-hourly average position of the ship by interpolation from daily data, by taking into account the geographic coordinates of each 3-hourly interval.

We also determined the 3-hourly R_{cp} values for $R_{cp} \le 0.5 \text{ GV}$, where the neutron intensity variation with R_{cp} is expected to be negligible. For the period January 31, 1996 to February 14, 1997, in the Antarctic region, in which $R_{cp} \le 0.5 \text{ GV}$, we computed R_{cp} by extrapolation of the dependence of R_{cp} on the geographic position observed in the 0.05–0.5 GV interval. Below we will evaluate the "apparent" cutoff rigidities, by taking into account the contribution of obliquely incident CR particles in a dipole approximation geomagnetic field.

5.4 Dependencies of Corrected CR Intensities upon Cutoff Rigidity

In Figs. 5.9 and 5.10 we show for the 3NM-IQSY and 2BC, respectively, the dependencies of the 3-hourly corrected values of normalized intensity $J = I/I_o$ (I_o is the average intensity at $R_{cp} < 1.0$ GV and for atmospheric mass $M_o = 1,034$ g cm⁻²).

For 3NM-IQSY $I_o = 3,30,556 \text{ counts} \times (3 \text{ hours})^{-1}$, for 2BC $I_o = 30,160 \text{ counts} \times (3 \text{ hours})^{-1}$ on R_{cp} for the northern (5.2–16.5 GV) and southern (0–16.5 GV) hemispheres, separately for the forward (from Italy to Antarctica) and backward (from Antarctica to Italy) surveys.

The "final" neutron data presented in Section 5.1 were obtained by applying all required corrections to the raw data; their daily averages were presented in Table A5.1 For the 3NM-IQSY it appears that the difference in *J* between forward and backward surveys is very small; only in the northern hemisphere is a systematic difference of ~1% observed for $R_{\rm cp} = 9-11$ GV, while for the 2BC the effect has a larger amplitude (~3%) and covers a wider rigidity interval (9–15GV). This anomaly (forward–backward effect, see Section 5.5) could be caused by the 180° rotation with the ship of the asymmetric distribution of matter near 3NM-IQSY and 2BC (see Section 5.1), relative to the asymmetric distribution of cutoff rigidities (so-called east–west effect). This is true for our survey in which the forward and return routes were almost coincident. When comparing the geomagnetic northern and southern hemispheres in the interval 5.2–16.5 GV (see Fig. 5.11), good agreement is found for the 3NM-IQSY data; this feature makes us confident of the correct determination of $R_{\rm cp}$.







For the 2BC detector, a systematic discrepancy is observed between the northern and southern curves $(J_N > J_S)$. This effect occurs in the same rigidity interval in which the large forward–backward effect is observed (see Fig. 5.10) and could be attributed to the use of vertical cutoff rigidities for the BC detector, for which a large nonvertical incidence contribution of primary CR is expected.

5.5 Forward–Backward Effect: CR East–West Asymmetry and Asymmetric Distribution of Neutron Absorption and Generation Around the Monitor

5.5.1 Forward–Backward Effect During CR Latitude Survey: Asymmetry in Cutoff Rigidities

The observed forward–backward effect in the northern hemisphere could be caused by the east–west asymmetry of CR (e.g., Janossy, M1950; Dorman, M1957, and Chapters 3 and 4, this volume), together with an asymmetric distribution of neutron generating and shielding matter around the 3NM-IQSY and 2BC detectors. On the basis of geographic coordinates, we determined the average azimuth angle φ_s of the ship's direction relative to the east. Since the main asymmetry in the distribution of matter is due to a higher superstructure behind the monitor (in the back of the ship), the forward–backward effect should be primarily caused by the difference in cutoff rigidities of particles arriving at the monitor at different zenith angles θ from the front of the ship, $R_f(\theta, t)$, and from the back, $R_b(\theta, t)$:

$$A_{\rm fb}\left(\theta,t\right) = \frac{2\left(R_{\rm f}\left(\theta,t\right) - R_{\rm b}\left(\theta,t\right)\right)}{R_{\rm f}\left(\theta,t\right) + R_{\rm b}\left(\theta,t\right)}.$$
(5.10)

At a point with a vertical cutoff rigidity R_{cp} in the real geomagnetic field, in dipole approximation we obtain

$$R_{\rm f}(\theta) = 4R_{\rm cp} \left\{ 1 + \left[1 - \left(R_{\rm cp} / R_{\rm max} \right)^{3/4} \sin \theta \cos \varphi_{\rm f} \right]^{1/2} \right\}^{-2} = 4R_{\rm cp} / \Gamma_{-}(\theta),$$
(5.11)

$$R_{\rm b}(\theta) = 4R_{\rm cp} \left\{ 1 + \left[1 + \left(R_{\rm cp} / R_{\rm max} \right)^{3/4} \sin \theta \cos \varphi_{\rm f} \right]^{1/2} \right\}^{-2} = 4R_{\rm cp} / \Gamma_{+}(\theta),$$
(5.12)

where R_{max} is the value of R_{cp} at the point where the ship crossed the CR equator, and $\varphi_{\text{b}} = \varphi_{\text{f}} + \pi$; therefore

$$A_{\rm fb}(\theta) = \frac{2\left[\Gamma_{+}(\theta) - \Gamma_{-}(\theta)\right]}{\Gamma_{+}(\theta) + \Gamma_{-}(\theta)}.$$
(5.13)

It is easy to see that when $\left| \left(R_{\rm cp} / R_{\rm max} \right)^{3/4} \sin \theta \cos \varphi_{\rm f} \right| << 1$, we approximately obtain

$$A_{\rm fb}(\theta) \approx \left(R_{\rm cp}/R_{\rm max}\right)^{3/4} \sin\theta\cos\varphi_{\rm f}.$$
 (5.14)

In Fig. 5.12 we show the changes (in %) of $A_{\rm fb}(\theta, t)$ during the survey for various θ values, as well as the change of $R_{\rm cp}(t)$.



Fig. 5.12 The expected difference $A_{\rm fb}(\theta, t)$, in cutoff rigidities of particles approaching the 3NM-IQSY detector at different zenith angles θ from the front and from the back of ship is plotted for $\theta = 15^{\circ}, 30^{\circ}, 45^{\circ}, 60^{\circ}$, and 75° (from thicker to thinner curves) respectively, together with cutoff rigidity $R_{\rm cp}(t)$ (dashed line) during the survey period. Abrupt variations in $A_{\rm fb}(\theta, t)$, are due to changes in the ship's direction inside ports

From Fig. 5.12 we can see that in the northern hemisphere in the forward leg of the survey, $A_{\rm fb}(\theta,t) > 0$, which means that $R_{\rm f}(\theta,t) > R_{\rm b}(\theta,t)$ (with the exception of a short time during which the ship was in Port Said). During the return trip in the northern hemisphere, we have the opposite situation and $A_{\rm fb}(\theta,t) < 0$. In this case, $R_{\rm f}(\theta,t) < R_{\rm b}(\theta,t)$. Since the additional shielding matter is primarily located at the back of the ship, the CR intensity, at equal $R_{\rm cp}$, should be larger on the return than on the forward route. To obtain quantitative estimations we need to determine the contribution of nonvertical incidence particles to the 3NM-IQSY counting rate.

5.5.2 Contribution of Nonvertical Incidence Particles to the 3NM-IQSY Counting Rate

Let us approximately compute the weight to the 3NM-IQSY counting rate of particles approaching from different zenith angles θ . We will consider only the generation of high-energy neutrons. The propagation of this type of neutrons was studied in detail by Dorman et al. (1999) by taking into account the attenuation and scattering processes. It was found that the "refraction effect" is important only for low energy neutrons ($E_n \leq 1 \text{ GeV}$). Then, in a first approximation, we will consider the propagation of high-energy neutrons in the same direction as that of the parent primary particles. The function $f_n(E_n, \theta)$ of neutron generation in the atmosphere in nuclear

interactions of primary CR particles is expected to be very close to the function $f_{\pi}(h, \theta)$ of pion generation (Dorman, M1957, M1972, M2004) and proportional to the primary particle flux (isotropic at the boundary of atmosphere at h = 0). Therefore we can assume that

$$f_{\rm n}(h,\theta) = A_{\rm n} \exp\left(-h/L_{\rm p} \cos\theta\right), \qquad (5.15)$$

where A_n is a constant and L_p is the attenuation length of the CR primary particles generating the neutron component detected at sea level ($L_p \approx 120 \text{ g.cm}^{-2}$). If L_n is the attenuation length of neutrons detected by the 3NM-IQSY, we obtain for the expected flux of neutrons arriving at the 3NM-IQSY at zenith angles from θ to $\theta + d\theta$, integrated on azimuth angle φ (for symmetrical azimuth distribution)

$$I(h_o, \theta) = \int_0^{h_o} f_n(h, \theta) \exp\left[-(h_o - h)/L_n \cos \theta\right] dh = 2\pi A_n L_p L_n \sin \theta \cos \theta$$
$$\times (L_n - L_p)^{-1} \left\{ \exp\left[-(h_o - h)/L_n \cos \theta\right] - \exp\left[-(h_o - h)/L_p \cos \theta\right] \right\}.$$
(5.16)

The attenuation length of neutrons L_n can be determined from our investigations in the Antarctic region and from the analytical approximation for the dependence of the barometric coefficient on cutoff rigidity according to Eq. 16.5.5 in Chapter 16 of the book Dorman (M2004) as

$$L_{\rm n} = -\beta_{\rm 3NM}^{-1} = -\beta_{\rm 2BC}^{-1} = -\beta_o \left[1 - \exp\left(-\alpha R_{\rm cp}^{-k}\right) \right], \tag{5.17}$$

where constants β_o , α , and *k* are given in Eq. 16.5.7 in Dorman (M2004) and are as follows:

$$\beta_o = -0.751\% / (g/cm^2), \quad \alpha = 5.69 \pm 0.03, \quad k = 0.411 \pm 0.002.$$
 (5.18)

Using the normalization condition

$$\int_{0}^{\pi/2} I(h_o, \theta) \,\mathrm{d}\theta = 1, \tag{5.19}$$

we can determine the constant A_n in Eq. 5.16. The normalized zenith angle distributions of $I(h_o, \theta)$ are shown in Fig. 5.13 for $R_{cp} = 0, 4, 8, 12, 16 \text{ GV}$, respectively.

It can be seen from Fig. 5.13 that the difference between zenith distributions $I(h_o, \theta)$ for different R_{cp} is very small. In Table 5.2 we list the expected weights of zenith zones as a function of R_{cp} and the average values for R_{cp} from 0 to 16 GV.

From Table 5.2 it can be seen that only two zones can be considered as the most important zones: $7.5-22.5^{\circ}$ (weight 0.482 at $R_{cp} = 0$ and 0.445 at $R_{cp} = 16$ GV) and 22.5–37.5° (weight 0.358 at $R_{cp} = 0$ and 0.376 at $R_{cp} = 16$ GV). We can see also



Fig. 5.13 The expected normalized neutron flux approaching the 3NM-IQSY detector as a function of zenith angle θ is plotted for cutoff rigidities $R_{cp} = 0.4, 8, 12$, and 16 GV, respectively (the last curve, marked by a thick line, corresponds to $R_{cp} = 16$ GV; the first to $R_{cp} = 0$ GV)

Table 5.2 Normalized weights of different zenith zones $\Delta\theta$ to the 3NM-IQSY counting rate for different cutoff rigidities R_{cp}

$\Delta \theta(^{\circ})$	Cutoff rigidities R_{cp} (GV)							Average		
	0	2	4	6	8	10	12	14	16	
0–7.5	0.0846	0.0839	0.0824	0.0809	0.0794	0.0781	0.0769	0.0758	0.0748	0.0797
7.5–22.5	0.4820	0.4796	0.4742	0.4686	0.4633	0.4583	0.4537	0.4494	0.4454	0.4639
22.5-37.5	0.3584	0.3598	0.3628	0.3658	0.3684	0.3709	0.3730	0.3749	0.3765	0.3678
37.5-52.5	0.0729	0.0744	0.0781	0.0819	0.0856	0.0892	0.0925	0.0957	0.0987	0.0854
52.5-67.5	0.0021	0.0022	0.0025	0.0028	0.0032	0.0035	0.0039	0.0042	0.0046	0.0032
67.5–90	5.0 E-06	5.7 E-06	7.7 E-06	1.0 E-05	1.4 E-05	1.8 E-05	2.2 E-05	2.7 E-05	3.3E-05	1.6 E-05

that with R_{cp} increasing from 0 to 16 GV, the relative weight of small zenith angle zones decreases (for zone 0–7.5° from 0.0846 at $R_{cp} = 0$ to 0.0748 at $R_{cp} = 16$ GV) and the relative weight of large zenith angle zones increases significantly (for zone 52.5–67.5° from 0.0021 at $R_{cp} = 0$ GV to 0.0046 at $R_{cp} = 16$ GV).

5.5.3 Forward–Backward Effect During CR Latitude Survey: Expected Asymmetry in Neutron Intensities

Figure 5.14 shows data on the expected asymmetry in neutron intensities $W_{\theta}^{av}A_{\rm fb}(\theta,t)$, obtained by using the coupling zonal coefficients W_{θ}^{av} -values computed in Section 5.5.2 for various zenith zones. The position of the shielding structure on the ship relative to the 3NM-IQSY detector is located such that zones at $\theta < 37.5^{\circ}$ are not shielded; zone $37.5-52.5^{\circ}$ is partially shielded, and zones at



Fig. 5.14 The weighted forward–backward asymmetry in cutoff rigidity for **a** zenith zones 7.5–22.5° (thin line), 22.5–37.5° (thick line), and 37.5–52.5° (very thick line) and **b** zenith zones 52.5–67.5° (thick line) and 67.5–90° (thin line) at sea level is plotted together with cutoff rigidity $R_{\rm cp}$ (dashed line) during the survey period

 $\theta > 52.5^{\circ}$ are all inside the shielded cone. Figure 5.13 shows that the 37.5–52.5° zone can result in a maximum of 4% (if totally shielded), while zones at $\theta > 52.5^{\circ}$ can provide only a maximum of 0.3%, which can be disregarded. If the structure in the back of the ship shields only one third of the particles arriving inside the western or eastern region of zenith zone $\theta > 37.5^{\circ}$, it will be enough to explain the forward–backward effect on the 3NM-IQSY counting rate.

For the 2BC detector, the most effective zone will also be $37.5-52.5^{\circ}$, but in this case the additional generation of neutrons in the shielding structure of the ship also could be important. In this way the forward–backward effect for the 2BC is expected to be larger than for the 3NM, in agreement with the observations. The simple averaging of the data between the forward and return routes will greatly reduce this effect, since the two routes are almost equal.
5.6 CR Intensity Versus Cutoff Rigidity, Analytical Approximation, and Coupling Functions for the 3NM-IQSY and 2BC Detectors

5.6.1 Analytical Description of the Dependence of the 3NM-IQSY and 2BC Intensities on the Vertical Cutoff Rigidity

Experimental data on the dependence of the 3NM-IQSY normalized intensity $J_{3NM}(R_{cp})$ at sea level upon R_{cp} have been presented in Figs. 5.9–5.11. To give an analytical description of $J_{3NM}(R_{cp})$ versus R_{cp} we use the function introduced by Dorman (1969):

$$J_{3\rm NM}(R_{\rm cp}) = I_{3\rm NM}(R_{\rm cp}) / I_{3\rm NMo} = 1 - \exp\left(-\alpha_{3\rm NM}R_{\rm cp}^{-k_{3\rm NM}}\right).$$
(5.20)

Constants α_{3NM} and k_{3NM} are obtained as regression coefficients of the best fit linear correlation between experimental quantities $\ln(-\ln(1-J_{3NM}(R_{cp})))$ and $\ln(R_{cp})$:

$$\ln\left(-\ln\left(1-J_{3\mathrm{NM}}\left(R_{\mathrm{cp}}\right)\right)\right) = -k_{3\mathrm{NM}}\ln\left(R_{\mathrm{cp}}\right) + \ln\left(\alpha_{3\mathrm{NM}}\right).$$
(5.21)

The regression is done on southern hemisphere data, which cover the total 0–16.5 GV rigidity interval. For determining the constants α_{3NM} and k_{3NM} , we use all data with $\ln(R_{cp}) > 1.5$; for smaller values of $\ln(R_{cp})$ the statistical fluctuations in $J_{3NM}(R_{cp})$ produce large fluctuations in $\ln(-\ln(1-J_{3NM}(R_{cp})))$. In this way the number of 3-hourly data samples in the southern hemisphere decreases from 542 to 200. The results of the determination of constants α_{3NM} and k_{3NM} are

$$\alpha_{3\rm NM}^S = 10.275 \pm 0.023, \ k_{3\rm NM}^S = 0.9615 \pm 0.0021 \tag{5.22}$$

with a correlation coefficient R = 0.99961. As a control, we analyzed northern hemisphere data (5.2–16.5 GV interval) and obtained, as expected, values consistent with those from the southern hemisphere:

$$\alpha_{3\rm NM}^N = 10.354 \pm 0.025, \ k_{3\rm NM}^N = 0.9621 \pm 0.0023 \tag{5.23}$$

with correlation coefficient R = 0.99940. For the southern hemisphere, the comparison between all 542 experimental 3-hourly data samples and values reconstructed by Eqs. 5.21 and 5.22 gives a very high correlation (R = 0.99937) for the total 0–16.5 GV rigidity interval.

For the 2BC data (see Figs. 5.11 and 5.12) we applied the same procedure as for 3NM-IQSY and obtained for the southern hemisphere

$$\alpha_{2BC}^{S} = 9.694 \pm 0.037, \ k_{2BC}^{S} = 0.9954 \pm 0.0038 \tag{5.24}$$

with a correlation coefficient R = 0.99875. For the 0–16.5 GV interval in the southern hemisphere, the correlation coefficient between experimental 2BC data and corresponding computed values is R = 0.9984.

5.6.2 Analytical Description of Coupling Functions for the 3NM-IQSY and 2BC Detectors

The coupling function W(R) for neutron detectors is defined as

$$W(R) = dJ(R) / dR \tag{5.25}$$

according to Dorman (M1957); here dJ (R) is the contribution of primary particles with rigidity between R and R + dR to the counting rate of a neutron monitor located at $R_{cp} < 1.0$ GV. The results of Section 5.6.1 showed that for the 3NM-IQSY detector, the analytical function described by Eq. 5.20 adequately represents the dependence of the counting rate on R_{cp} for both hemispheres by using the α_{3NM} and k_{3NM} values obtained in the southern hemisphere, using Eq. 5.21. Also for the 2BC detector, more accurate estimates of α_{2BC} and k_{2BC} are obtained in the southern hemisphere, but they adequately represent the dependence of the 2BC counting rate on R_{cp} for both hemispheres. Then the normalized coupling function (so-called Dorman function) will be

$$W(R) = \alpha k R^{-(k+1)} \exp\left(-\alpha R^{-k}\right), \qquad (5.26)$$

with $\alpha = 10.275$, k = 0.9615 for 3NM-IQSY detector and $\alpha = 9.694$, k = 0.9954 for 2BC detector. The coupling functions computed for the 3NM and 2BC data are shown in Fig. 5.15, together with the relative standard errors. The relative standard errors were determined according to the relation

$$\left(\frac{\sigma(W)}{W}\right)^2 = \left(\frac{\sigma(\alpha)}{\alpha}\right)^2 + \left(\frac{\sigma(k)}{k}\right)^2 + \left(\frac{\sigma(k)}{\ln R}\right)^2 + \left(\frac{\sigma(\alpha)}{R^{-k}}\right)^2 + \left(\frac{\alpha\sigma(k)}{R^{-k}\ln R}\right)^2.$$
(5.27)

From Fig. 5.15 we can see that the 2BC detector is significantly more sensitive to lower primary energy particles than the 3NM-IQSY detector, as expected. We point out that the estimated standard errors do not take into account possible systematic errors due to an inadequate evaluation of threshold rigidities; in particular, a significant contribution from nonvertical incidence particles can be anticipated for the 2BC detector.

5.7 Effective Cutoff Rigidities for Different Zenith and Azimuth Angles of CR Arriving at Points Along the Ship Route

In Section 5.6 we used cutoff rigidities computed for vertical incidence particles. However, since 3NM-IQSY and 2BC neutron detectors are also sensitive to nonvertical incidence primary particles, it is necessary to compute effective cutoff rigidities (taking into account penumbra) for different zenith and azimuth angles of CR



Fig. 5.15 a Differential response functions W(R) in %/GV for 3NM-IQSY (thick line) and 2BC (thin line) for 1996/97 latitude survey Italy–Antarctica, **b** Relative error of $\sigma(W)/W$ for 3NM-IQSY (thick line) and 2BC (thin line)

arriving at points along the ship's route. These calculations were made in Danilova et al. (2001) for the ship's route from Italy to Antarctica (the first 38 days of expedition 1996/97) and in Danilova et al. (2003) for the ship's route from Antarctica to Italy (days 59–96 of expedition).

5.7.1 Calculation of Effective Cutoff Rigidities for Different Zenith and Azimuth Angles of CR Arriving at Points Along the Ship Route from Italy to Antarctica

In Danilova et al. (2001), cutoff rigidities of nonvertically incident CR particles have been calculated using a numerical trajectory method (McCracken et al., M1962) everyday for the corresponding average geographic location of the ship. Computations were done by considering the earth's total magnetic field as the sum of fields

generated by both internal and external sources. The main geomagnetic field from internal sources is represented by a Gaussian series with the International Geomagnetic Reference Field 1995 coefficients (IAGA Division V, Working Group 8, 1996) up to n = 10, extrapolated to the epoch of the survey. Note that the secular variation of the main geomagnetic field is too small to affect the results of calculations during the survey time. The magnetic field from external sources is represented by the magnetospheric magnetic field model developed by Tsyganenko (1989). It takes into account the contribution from (1) ring current, (2) the magnetotail current system including the plasma sheet current and return currents, and (3) magnetopause currents as well as the large-scale system of field-aligned currents. Calculations were done for a quiet magnetosphere ($K_p = 0$), corresponding to the "quiet" solarinterplanetary conditions observed during the survey period. For each point we computed the upper cutoff rigidity $R_{\rm c}$, which is the rigidity value of the highest detected allowed/forbidden transition among the computed trajectories (e.g., Cooke et al., 1991), and the lowest cutoff value $R_{\rm L}$, which is the rigidity value of the lowest allowed/forbidden transition. A trajectory was considered "forbidden" if its asymptotic longitude is bigger than 1000°. Calculations have been done for 0.001 GV steps. The effective cutoff rigidity R_{cp} is defined by the equation

$$\sum_{j=R_{\rm cp}}^{R_{\rm c}} W_j \Delta R_j = \sum_{i=R_{\rm L}}^{R_{\rm c}} W_i \Delta R_i (\text{allowed}), \qquad (5.28)$$

where W_i is the coupling function in the ΔR_i interval. Under the reasonable hypothesis of a flat W_i in the $R_L - R_c$ interval (flat CR spectrum approximation, e.g., Shea et al., M1976), we obtain

$$R_{\rm cp} = R_{\rm c} - \Delta R_{\rm cp} \cong R_{\rm c} - \sum_{i=R_{\rm L}}^{R_{\rm c}} \Delta R_i (\text{allowed}).$$
(5.29)

For this calculation we used $\Delta R_i = 0.01 \,\text{GV}$ intervals.

We also calculated the diurnal variations of vertical cutoff rigidities R_v for each day and found that they are smaller than 0.1 GV at geographic latitudes 40°N–40°S and smaller than 0.15 GV at latitudes 40°–53°S. At every point, the R_v value at 12 LT was nearly equal to the daily average. Assuming that this result could also be extended to inclined particles, we calculated the effective cutoff rigidities at 12 LT.

The results of computation of effective cutoff rigidities along the survey from Italy to Antarctica (first 39 days) at different zenith angles $\theta = 0^{\circ}$, 15° , 30° , 45° , 60° for azimuth angles 0° and 45° of incident CR particles are given in Table A5.2; at the same zenith angles but for azimuth angles 90, 135 and 180° – in Table A5.3, and for azimuth angles 225, 270, and 315° – in Table A5.4. Figures 5.16 and 5.17 show examples of cutoff rigidity behavior during different days of the latitude survey, from 355 of 1996 to 27 of 1997. The geomagnetic field anomaly encountered on the fourth day of the survey is remarkable (Fig. 5.16), and is discussed by Dorman et al. (2000).



Fig. 5.16 Effective cutoff rigidity profiles computed for the first 15 days of survey (northern hemisphere, from day 355 of 1996 up to day 3 of 1997) for different zenith angles and opposite azimuth angles $\varphi = 45^{\circ}$ and 225°



Fig. 5.17 Effective cutoff rigidity profiles computed for days 4–27 of 1997 of the survey (southern hemisphere) for different zenith angles and opposite azimuth angles $\varphi = 45^{\circ}$ and 225°

5.7.2 Effective Cutoff Rigidities for Different Zenith and Azimuth Angles for the Ship Route from Antarctica to Italy

The corresponding results of Danilova et al. (2003) of the computation of effective cutoff rigidities for days 48–56 and 60–85 of 1997 along the survey from Antarctica to Italy at different zenith angles $\theta = 0^{\circ}$, 15° , 30° , 45° , 60° for azimuth angles $\varphi = 0^{\circ}$ and 45° of incident CR particles are given in Table A5.5; at the same zenith angles but for azimuth angles $\varphi = 90^{\circ}$, 135° , and 180° in Table A5.6, and for azimuth angles $\varphi = 225^{\circ}$, 270° , and 315° in Table A5.7.

Figures 5.18 and 5.19 show several examples of the effective cutoff rigidities behavior for different zenith and azimuth angles during days of latitude survey 48–56



Fig. 5.18 Effective cutoff rigidities for different azimuth angles φ and for different zenith angles θ during days 48–56 and 60–71 of 1997 of the latitude survey (According to Danilova et al., 2003)



Fig. 5.19 The dependencies of effective cutoff rigidities from latitude for different azimuth angles φ and different zenith angles θ (According to Danilova et al., 2003)

and 60–71 of 1997 (CR data for days 57–59 of 1997 are not available because of very bad stormy weather), when the ship *Italica* was in the southern hemisphere.

From Fig. 5.18 it can be seen that the biggest difference in cutoff rigidities is in the east-west direction (the well-known east-west CR asymmetry). From this Figure it can be also seen that in the region of latitudes \sim (14–21°) S and longitudes

(~85–95°) E, the gradual dependencies of cutoff rigidities from zenith angle θ are sufficiently disturbed (about the same disturbances can be seen in Figs. 5.1 and 5.2 of the paper by Bieber et al., 1997).

The dependencies of effective cutoff rigidities for different zenith and azimuth angles from latitude are shown in Fig. 5.19.

5.8 Apparent Cutoff Rigidities Along the Ship's Route and Related Coupling Functions for the 3NM-IQSY and 2BC Detectors

5.8.1 Calculation of Apparent Cutoff Rigidities R^{ap}_{cp} along the Ship's Route: Dipole Approximation for Inclined Directions

In Section 5.6 we used cutoff rigidities computed for vertical incidence particles. However, since a neutron monitor is also sensitive to nonvertical incidence primary particles, it is necessary to compute the "apparent" cutoff rigidities (see Clem et al., 1997) by taking into account cutoff rigidities not only for vertically incident particles, but also for nonvertical incidence primary particles with different weights as a function of zenith angle:

$$R_{\rm cp}^{ap}\left(R_{\rm cp}\right) = \frac{\int\limits_{0}^{2\pi} d\varphi \int\limits_{0}^{\pi/2} R_{\rm cp}\left(\theta,\varphi\right) W\left(R_{\rm cp},\theta,\varphi\right) d\theta}{\int\limits_{0}^{2\pi} d\varphi \int\limits_{0}^{\pi/2} W\left(R_{\rm cp},\theta,\varphi\right) d\theta}$$
(5.30)
$$= \sum_{i} \left\langle R_{\rm cp}\left(\theta_{i}-\theta_{i-1}\right) \right\rangle \left\langle W\left(R_{\rm cp},\theta_{i}-\theta_{i-1}\right) \right\rangle,$$

where $\langle R_{cp}(\theta_i - \theta_{i-1}) \rangle$ is the cutoff rigidity averaged over the azimuth angle in the zenith zone $\theta_i - \theta_{i-1}$ and $\langle W(R_{cp}, \theta_i - \theta_{i-1}) \rangle$ is the normalized relative weight of this zone.

Clem et al. (1997) and Stoker et al. (1997) discussed the problem of apparent cutoff rigidities. In these papers the authors proposed performing complete trajectory calculations by taking into account scattering of neutrons in the atmosphere. They showed that for $R_{\rm cp} < 6-7 \,\rm GV$ apparent cutoff rigidities are about the same as vertical ones, but with increasing $R_{\rm cp}$ the difference $R_{\rm cp}^{ap} - R_{\rm cp}$ increases up to 0.7–0.8 GV at $R_{\rm cp} = 16 \,\rm GV$. Dorman et al. (1999) showed that scattering is important for low-energy solar neutrons, while for high-energy neutrons as detected by neutron monitors, scattering seems to be less important and a one-dimensional cascade model can be used. On the basis of the results given in Section 5.5, in which we determine the normalized zenith angle distribution of neutrons arriving at the

3NM-IQSY detector for an isotropic distribution of CR primary particles over the atmosphere, we can compute the expected weights of six zenith zones to the 3NM counting rate as a function of R_{cp} . For calculations of apparent cutoff rigidities, we also used the information on integral multiplicities of secondary neutrons detected by neutron monitor in dependence of zenith angle of incoming primary CR particles. This information is based on the theoretical calculations of meson-nuclear cascades of primary protons with different rigidities arriving at the earth's atmosphere at zenith angles 0°, 15°, 30°, 45°, 60°, and 75° (Dorman and Pakhomov, 1979). The results of Dorman and Pakhomov (1979) have been checked and normalized by using the coupling functions obtained in Dorman et al. (2000). As a result, we obtained the following weights in dependence of R_{cp} :

$$W_{0-7.5}(R_{\rm cp}) = 0.084812 - 0.000645R_{\rm cp}, \tag{5.31a}$$

$$W_{7.5-22.5}\left(R_{\rm cp}\right) = 0.48305 - 0.00240R_{\rm cp},\tag{5.31b}$$

$$W_{22.5-37.5}(R_{\rm cp}) = 0.35829 + 0.001194R_{\rm cp}, \tag{5.31c}$$

$$W_{37.5-52.5}\left(R_{\rm cp}\right) = 0,071925 + 0.0016917R_{\rm cp},\tag{5.31d}$$

$$W_{52.5-67.5}\left(R_{\rm cp}\right) = 0.001925 + 0.000161R_{\rm cp},\tag{5.31e}$$

$$W_{67.5-90}(R_{\rm cp}) = 4.789 \times 10^{-7} + 4.003 \times 10^{-8} R_{\rm cp}.$$
 (5.31f)

By using the same procedure given in the Section 5.5 for computing nonvertical incidence cutoff rigidities from front and back directions relative to the ship's orientation, we calculate along the survey route the nonvertical incidence cutoff rigidities $R_{\rm cp}(\theta, \varphi, t)$ from six additional azimuth directions φ : front left, left, left back, back right, right, and right front for the same zenith angles. We use the computed $R_{\rm cp}(\theta, \varphi, t)$ for determining the average values $R_{\rm cp}^{av}(\theta, t)$. In Fig. 5.20 we show $R_{\rm cp}^{av}(\theta, t) - R_{\rm cp}$ versus $R_{\rm cp}$ for all 3-hourly survey intervals.

 $R_{cp}^{av}(\theta,t) - R_{cp}$ versus R_{cp} for all 3-hourly survey intervals. Using Eqs. 5.30 and 5.31a–5.31f, and by means of $R_{cp}^{av}(\theta,t)$ computed for zenith angles of 15, 30°, 45°, 60°, and 75°, we determined R_{cp}^{ap} . From Fig. 5.21, in which we show $R_{cp}^{av}(\theta,t) W \left(R_{cp}, \theta_i - \theta_{i-1}\right)$ for each 3-hourly interval of the survey period, we can see that major contributions of $R_{cp}^{av}(\theta,t) W \left(R_{cp}, \theta_i - \theta_{i-1}\right)$ to R_{cp}^{ap} come from the zenith zones 7.5–22.5° (43.4% of total value of R_{cp}^{ap}) and 22.5–37.5° (38.2%).

The dependence $R_{cp}^{av}(\theta,t) - R_{cp}$ versus R_{cp} , which is shown in Fig. 5.22, can be approximated by

$$R_{\rm cp}^{av}(\theta,t) - R_{\rm cp} = 0.00260 R_{\rm cp}^2 - 0.01258 R_{\rm cp} + 0.00922 \,\rm GV \tag{5.32}$$

with correlation coefficient R = 0.9986. This dependence is in agreement with the Clem et al. (1997) average computations obtained by using the local geomagnetic field for selected sites.



Fig. 5.20 The behavior of the difference between $R_{cp}^{av}(\theta,t)$ and R_{cp} : **a** as a function of survey time and **b** as a function of R_{cp} for different zenith angles θ (from *top* to bottom: $\theta = 75^{\circ}$, 60° , 45° , 30° , 15°) of incoming particles (According to Dorman et al., 2000)

5.8.2 Calculation of Apparent Cutoff Rigidities in the Real Geomagnetic Field for the Ship Route Italy–Antarctica Taking into Account Results of Trajectory Calculations for Inclined Directions

In Dorman et al. (2001), we calculate the apparent cutoff rigidities of the latitude survey from Italy to Antarctica. Computations were done for the forward route of the survey, based on the results of Danilova et al. (2001) on trajectory calculations for inclined cutoff rigidities at eight azimuths φ (every 45°) and five zeniths angles θ (every 15°), described in Section 5.7.



Fig. 5.21 Panel **a**: the behavior of the weighted average cutoff rigidity $R_{cp}^{av}(\theta, t) W \left(R_{cp}, \theta_i - \theta_{i-1}\right)$ for different zenith zones: 0–7.5° (curve 1), 7.5–22.5° (curve 2), 22.5–37.5° (curve 3), 37.5–52.5° (curve 4), 52.5–67.5° (curve 5), and 67.5–90° (curve 6), as a function of survey time. Panel **b**: the behavior of R_{cp}^{ap} (thick line), R_{cp} (thin line), and $R_{cp}^{ap} - R_{cp}$ (dashed line), as a function of survey time



Fig. 5.22 The behavior of $R_{cp}^{av}(\theta, t) - R_{cp}$ as a function of R_{cp} , computed for all 3-hourly intervals of survey



Fig. 5.23 The behavior of $R_{cp}^{ap}(\theta, t) - R_{cp}$ as a function of R_{cp} , computed for the forward part of the latitude survey in 1996/97: southern hemisphere (solid circles), northern hemisphere (open diamonds) (According to Dorman et al., 2001)

In Table A5.8 we give the results of computation of the average (over azimuth angle) cutoffs for different zenith angles, and in Table A5.9 are listed the computed weights, together with the resulting apparent cutoffs.

In Fig. 5.23 we show the dependences of $R_{cp}^{ap}(\theta, t) - R_{cp}$ versus R_{cp} for the northern and southern hemispheres.

5.8.3 Calculation of Apparent Cutoff Rigidities in the Real Geomagnetic Field for the Ship Route Antarctica–Italy Taking into Account Results of Trajectory Calculations for Inclined Directions

In Dorman et al. (2003), we calculate the apparent cutoff rigidities of the latitude survey from Antarctica to Italy. Computations were done for the backward route of the survey on the basis of results of Danilova et al. (2003) on trajectory calculations for inclined cutoff rigidities at eight azimuths φ (every 45°) and five zeniths angles θ (every 15°), described in Section 5.7. In Table A5.10, we give results of computation of the average (over azimuth angle) cutoffs for different zenith angles. In Table A5.11 are listed the computed weights, together with the resulting apparent cutoffs for the backward part of latitude survey in 1996/97. In Fig. 5.24 we show the dependence of $R^{ap}(\theta,t) - R_{\text{eff}}$ versus R_{eff} obtained on the basis of observation data for the forward and backward parts of latitude survey in 1996/97.



Table 5.3 Constants α_{3NM} , k_{3NM} , α_{2BC} , k_{2BC} obtained for R_{cp} and R_{cp}^{ap} dependencies

Dependence from	α_{3NM}	k _{3NM}	Correlation coefficient for all 542 3-hourly data		
R _{cp}	10.275 ± 0.023	0.9615 0.0021	0.99937		
$R_{\rm cp}^{ap}$	9.916 ± 0.021	0.9393 0.0020	0.99939		
Dependence from	α_{2BC}	k _{2BC}	Correlation coefficient for all 390 3-hourly data		
R_{cp} R_{cp}^{ap}	9.694 ± 0.037 $9.344 \ 0.036$	0.9954 ± 0.0038 0.9725 ± 0.0037	0.99884 0.99887		

5.8.4 Comparison of Latitude Dependencies and Coupling Functions for Effective R_{cp} and Apparent R^{ap}_{cp} Cutoff Rigidities

By using the same method as described in Section 5.6, we determined the coupling functions for the 3NM and 2BC neutron detectors when the apparent cutoff rigidities R_{cp}^{ap} are considered for southern hemisphere data. Table 5.3 lists the values of constants α_{3NM} , k_{3NM} , α_{2BC} , k_{2BC} obtained for R_{cp} and R_{cp}^{ap} dependencies, respectively.

It can be seen that the differences are rather small, as shown in Fig. 5.25, where the coupling functions for the NM obtained by the two methods are compared.



Fig. 5.25 Differential NM coupling (response) functions for 1996/97 survey, as computed by using cutoff rigidities R_{cp} (solid line) and R_{cp}^{ap} (dashed line) (According to Dorman et al., 2000)

5.9 Summary of Results of the CR Latitude Survey on the Ship *Italica* in 1996/97, and Discussion on Coupling Functions

5.9.1 Main Results Obtained in CR Latitude Survey in 1996/97 on Board the Ship Italica

We summarize the results of the Italian CR Antarctic survey in 1996/97:

- The quality of the 3NM-IQSY data recorded during the survey has been controlled in detail; the instrumental stability of both monitors has been successfully verified by calibrations with the Rome 17NM-IQSY before and after the survey, and by internal tests conducted during the expedition, including ratios among individual counter's intensities, multichannel pulse analyses, etc.
- 2. Intensity data have been accurately corrected for a number of meteorological effects described in detail in Chapter 16 of Dorman (M2004) including the effect of atmospheric mass variations, ship oscillations, and atmospheric temperature changes; the absorbing atmospheric mass has been estimated by barometric data, taking into account the wind effect and the local value of gravitational acceleration.
- 3. Intensity data have been corrected for changes in the primary CR flux, including north–south anisotropy.
- 4. The 3NM-IQSY corrected data, recorded along the same route during forward and return trips, i.e., with temporal separation and under different meteorological conditions, are statistically consistent within $(1.0-1.6)\sigma$; a small systematic discrepancy is observed in the rigidity interval $R_{cp} = 9-11$ GV. In Section 5.5 we showed that this effect could be attributed to the asymmetric shielding of the

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monitor (forward-backward effect). Owing to its small amplitude, we eliminated this effect by averaging the forward and return data.

- 5. Cutoff rigidities have been computed by taking into account the penumbra effect for vertically incident particles, for the 1995 geomagnetic field model extrapolated to the survey period, and by using, as a first approximation, a flat coupling function in the penumbra region (e.g., Shea et al., M1976). To maximize accuracy, it is necessary to compute the apparent cutoff rigidity thresholds R_{cp}^{ap} , by taking into account the contribution of nonvertically incident primary particles in the actual geomagnetic field (e.g., Clem et al., 1997) and evaluating the penumbra effect for the actual coupling functions. For computing such relatively small effects we used, as a first approximation, a simplified algorithm adapted for a dipole geomagnetic field. $R_{cp}^{ap}R_{cp}$ was found to be negligible for $R_{cp} < 5 \text{ GV}$ and to increase up to 0.5 GV at $R_{cp} = 16 \text{ GV}$, in general agreement with Clem et al. (1997).
- 6. We note that in our survey the penumbra effect is particularly important in the northern hemisphere. The 2BC detector, which is sensitive to thermalized neutrons, should have a larger response function for primary particles arriving at large zenith angles, as compared with the 3NM-IQSY. In this case, the weights of penumbra and forward–backward effects are expected to be more relevant for the 2BC, as indicated by a large discrepancy between the northern and southern hemispheres and a remarkable forward–backward effect.
- 7. The measured 3NM-IQSY latitude curves in both hemispheres are equal within statistical limits.
- 8. The 3NM-IQSY coupling function, computed using data recorded in the southern hemisphere covering the whole rigidity interval, can be reliably used for the data of the sea-level NM station network during the past solar minimum.
- 9. We applied the same procedure for the 2BC detector and computed the coupling function for the thermalized neutron flux in the atmosphere at sea level. As far as we know, this is the first detailed evaluation of such a coupling function: the 2BC detector on the ocean is found to respond to somewhat lower energy particles than the 3NM-IQSY detector, as expected. We point out that this coupling function can be used for a 2BC operating on the ground provided that the different contribution of radioactivity (from seawater to ground) is taken into account.

5.9.2 Comparison and Discussion on Coupling Functions

Let us now compare the 3NM-IQSY results of the latitude survey in the 1996/97 solar activity minimum with previous results obtained by Moraal et al. (1989) for the 1986/87 solar minimum. This comparison should be done by applying the same procedures on the 3NM-IQSY data: (1) the same cutoff rigidity thresholds, in this case estimated for the vertical particle incidence by taking into account the penumbra effect, and (2) the same analytical data treatment. We note that our 3NM-IQSY data have been corrected for some small effects which apparently have not been



Fig. 5.26 Comparison between normalized neutron intensities as a function of cutoff rigidity R_{cp} for the latitude survey 1996/97 for the southern hemisphere (diamonds), and the 1986/87 survey (solid line) (According to Moraal et al., 1989)

taken into account by Moraal et al. (1989): sea-state fluctuations, the wind effect, and pole-to-equator changes in atmospheric temperature. Figure 5.26 shows the 3-hourly values of our survey together with the Moraal et al. (1989) latitude curve as a function of vertical cutoff rigidity. Both latitude curves in Fig. 5.26 have been normalized to the average intensity at $R_{cp} < 1.0 \,\text{GV}$. It appears that the results of the two surveys performed during two subsequent solar minima are in close agreement. The pole-to-equator intensity ratios are equal, and only two small differences are observed in the comparison of the latitude curves: the data of the latitude survey 1996/97 are higher than those of 1986/87 ones by 1% in the intervals 3-5 GV and 7–10 GV. The problem of the existence of the "crossover" effect, when comparing coupling functions obtained in subsequent solar minima (Moraal et al., 1989; Reinecke et al., 1997; Bieber et al., 1997), can be clarified only by using the same and complete data treatment (corrections for atmospheric absorption, by taking into account changes in gravity g and wind effect; corrections for sea-state and temperature effects, as well as for primary variations and north-south CR asymmetry), and cutoff rigidities computed by taking into account the contribution of nonvertical incidence particles and the penumbra effect also for nonvertical incidence particles. Moreover, we think that the NM station data could help in disentangling the problem of crossover by considering that the efficiency of neutron monitor stations is usually rather constant, within $\sim 0.1\%$, even for a solar-cycle time span.



Fig. 5.27 Comparison between differential response functions, for the 1996/97 latitude survey (thick line) and for the 1986/87 survey (thin line) (According to Moraal et al., 1989)

As a result, a negligible "crossover" effect is found when comparing the 1986/87 and 1996/97 coupling functions (see Fig. 5.27), and it is opposite to the large crossover found by Bieber et al. (1997) when comparing the Moraal et al. 1986/87 survey with their 1995 survey. It is important to note that the CR intensity at high latitude during the 1995 survey was lower by 0.3–1% than during 1996/97 survey.

A difference in coupling functions, as reported for subsequent solar minima in previous papers (Moraal et al., 1989; Bieber et al., 1997), would correspond to an anomalous difference of 3–4% between intensity changes observed in successive solar minima, when comparing stations located at very low cutoff rigidity with stations with cutoff near the crossover point ($\approx 6-7$ GV). The CR intensity at $R_{cp} \leq 2.4$ GV (according to NM data of Oulu, Kiel, and Calgary stations) was higher in 1986/87 than in 1996/97 (our survey time) by $\delta I_{OKC} \approx 1\%$; the simultaneous change observed at $R_{cp} = 6.2$ GV (Rome station) was $\delta I_R \approx 0.6\%$. Thus, the behavior of NM-IQSY stations appears to be inconsistent with the existence of a crossover effect and supports the similarity of the 1986/87 and 1996/97 coupling functions found in Dorman et al. (2000). We notice that no evidence of a crossover effect has been found when analyzing neutron monitor airborne surveys in two consecutive solar minima (Stoker and Moraal, 1995). Anyway, we think that the problem of crossover is still open, and a more detailed investigation is needed.

Chapter 6 Geomagnetic Variations of Cosmic Rays

6.1 Two Main Sources of CR Geomagnetic Variations

In this chapter we shall deal with the CR variations caused by variations of the geomagnetic field. Changes in this field may be connected with processes in the earth's interior (for instance, the well-known phenomenon of the earth's magnetic field inversions, moving of magnetic poles, geomagnetic secular variations), or with electrical currents in the earth's ionosphere and magnetosphere, controlled mostly by solar activity. What are the direct influences of each of these field variations on CRs and particularly on the cutoff rigidities and the asymptotic directions of incidence? Of course, the influence of the secular geomagnetic field variations due to internal sources may be determined by the trajectory-tracing method described in Chapter 3 (if the long-term time-variation of the space distribution of the geomagnetic field is known). The change of the planetary distribution of CR cutoff rigidities in the present epoch of direct CR continuous measurements by a NM network was considered in detail in Section 3.8. The experimental and theoretical data showing that there are long-term (thousands of years) variations of CR intensity due to variations of the interior sources of the field, will be considered in Sections 6.2–6.5.

For sources in the earth's magnetosphere are very important detail information on radiation belts and electrical currents in the magnetosphere and their connection with the processes in the ionosphere (Sections 6.6–6.13). These currents change the magnetic field and, correspondingly, CR cutoff rigidities. In order to take into account the geomagnetic field variations due to ring currents in the magnetosphere, it is important to compute not only the variation of the vertical cutoff rigidity in the real field in the presence of a thin ring current, but also to estimate the change of threshold rigidities for particles incident under various zenith angles, and to consider the widening of the current in latitude, and to estimate the effect of volume currents. Also, the influence of the confinement and asymmetry of the geomagnetic field by the action of the solar-wind plasma must be taken into account. These current systems and changes of the magnetosphere also influence the asymptotic directions and the acceptance cones of the particles. The observed CR variations arising

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from changes in the geomagnetic field caused by exterior sources are considered in Section 6.14. In Sections 6.15 and 6.16 we discuss the experimental data and the possible nature of the so-called local solar-daily and lunar-daily CR variations, respectively. The first type of CR anisotropy possibly due to an asymmetry of the magnetosphere, and second type may be connected with the tidal phenomenon in the earth's magnetosphere but which may also be spurious, due to a complex amplitudephase modulation (with a period of about 27 days) of the solar CR anisotropy. The observations in the high-latitude region show considerable anomalies in the cutoff rigidities. Here the influence of the tail of the earth's magnetosphere on the CR, which should be strongly felt in the high-latitude region, offers a promising explanation (see Section 6.17).

In Section 6.18 we consider how CR variations of geomagnetic origin may be discriminate from observing data by using spectrographic method. The big changes of cutoff rigidities and geomagnetic CR variations during magnetic storms are considered in Sections 6.19–6.23. The simplest version of the global spectrographic method (BDY-method) for discriminating of CR magnetospheric variations is considered in Section 6.24, and its application to analysis of NM network CR data in Section 6.25. In Chapter 7 we consider in detail the Tsyganenko-89 model – widely used for CR trajectory calculations – and its development, and the checking magnetospheric models by CRs.

6.2 CR Variations Expected for Large Long-Term Changes of the Geomagnetic Field

6.2.1 Expected CR Variations Caused by Changing of the Earth's Dipole Magnetic Moment

Paleomagnetic investigations show that during the last 3.6 million years the magnetic field of the earth changed sign nine times (Cox et al., 1967). Hence, it is plausible that the earth's magnetic moment has changed considerably, especially near the times of sign changes, paleomagnetic data show that in these periods the magnetic moment may have had nearly one-fifth of the present value. Of course, this must lead to considerable variations in CR intensity. At times when the poles are interchanged, the CR intensity will become much greater, and this again must lead to an increase in the frequency of spontaneous mutations and an acceleration of the evolution in these periods. Important information about variations of CR intensity in far-off epochs can be obtained by the method of atmospheric cosmogenic isotopes (see Chapters 10 and 17 in Dorman, M2004). Variations of extraterrestrial origin, affecting the CR intensity in the interplanetary space, may be excluded by looking at the data from meteoritic isotopes. The expected variation in the rate of formation of ¹⁴C in the earth's atmosphere with variations of the magnetic moment of the earth was computed by Wada and Inoue (1966). Let the number of ¹⁴C atoms formed in the terrestrial atmosphere by one primary particle with rigidity R be m(R)

(multiplicity of generation), D(R,t) the primary spectrum, then the number of ¹⁴C atoms formed in 1 sec in an air column of 1 cm² cross section above the point with cutoff rigidity R_c will be

$$Q(R_{\rm c},t) = \int_{R_{\rm c}}^{\infty} m(R) D(R,t) \,\mathrm{d}R. \tag{6.1}$$

The dependence of Q on R_c can be easily found from measurements of the spectrum and a captured cross section of secondary neutrons (Soberman, 1956; Lingenfelter, 1963: see for details Chapter 17 in Dorman, M2004). Further, in dipole approximation

$$R_{\rm c} = 14.9 \left(M/M_o \right) \cos^4 \lambda, \tag{6.2}$$

where M_o is the present magnetic moment of the earth. Let \overline{Q} be the rate of formation of ¹⁴C, expressed in the same units, averaged over the entire earth. Then, by substituting Eq. 6.2 into Eq. 6.1, considering the results of Soberman (1956) and Lingenfelter (1963) and averaging, we find the expected dependence of $\overline{Q}/\overline{Q}_o$ on M/M_o . Figure 6.1 gives the computed values of $\overline{Q}/\overline{Q}_o$ for the level of extraterrestrial intensity at the solar minimum in 1953/54 and the maximum in 1957/58 as obtained by Soberman (1956) and Lingenfelter (1963).

Values computed by Wada and Inoue (1966) with inclusion of non-dipole terms according to Quenby and Webber (1959) and Kondo et al. (1965) are also shown in Fig. 6.1(Q-W and K-K, correspondingly). The differences arising from changes



Fig. 6.1 Relation between the production rate $\overline{Q}/\overline{Q}_o$ of ${}^{14}C$ and the geomagnetic dipole moment M/M_o . Here \overline{Q} is the average value all over the earth's surface, \overline{Q}_o and M_o correspond to the time 1953–1958 (According to Wada and Inoue, 1966)

in solar activity or from different representations of the geomagnetic field are seen to be less than a few percent. On the other hand, if the magnetic moment is decreased 10 times, the rate of ¹⁴C formation computed in Wada and Inoue (1966) is increased by a factor of 2 and an increase of the magnetic moment by a factor of 10 leads to a decrease in the rate of ¹⁴C formation by a factor of 3.5–3.6. The relatively small increase in the rate of ¹⁴C formation for a considerable decrease of *M* is due to the fact that about 40–50% of ¹⁴C is formed by primary CR particles with rigidity R > 15 GV, which are only weakly influenced by the geomagnetic field. Ramaty (1967) similarly found

$$\overline{Q}/\overline{Q}_o \propto (M/M_o)^{-0.5} \tag{6.3}$$

for small variations of M/M_o , in good agreement with the slope in Fig. 6.1 near $M/M_o \approx 1$.

6.2.2 Variations of Geomagnetic Origin During the Last 2,000 Years

The CR variations during the last 2,000 years were investigated by Kigoshi et al. (1965) by measuring the relative ¹⁴C abundance in year rings of an old cedar in southern Japan. Figure 6.2 gives the results of the measurements as well



Fig. 6.2 ¹⁴C content of tree ring dated samples and computed variations in atmospheric radiocarbon concentration based on the variation in geomagnetic dipole moment (According to Kigoshi et al., 1965)



Fig. 6.3 Observed intensity of equatorial geomagnetic force in ancient times and assumed smooth variation. Case A, assumed variation for better agreement with observed atmospheric ¹⁴C variation; Case B, assumed variation given by Nagata as an average of observed values (From Kigoshi et al., 1965)

as the ¹⁴C variations expected on the assumption that CR intensity changes only by the variations of the geomagnetic field.

The variations of the earth's magnetic field are known from paleomagnetic data (Fig. 6.3) according to which the magnetic moment of the earth about 2,000 years ago had approximately 1.5 times the present value, and about 6,000 years ago half its present value.

Figure 6.3 shows that the measured values of 14 C and the paleomagnetic field can be made to agree with each other.

6.2.3 Secular Variations of the Cutoff Rigidities

The secular variations of the geomagnetic field cause a slow variation of the cutoff rigidities. As shown by Gall (1960, 1962), these variations may reach a few percent, but during the period 1845–1955 the variation of the cutoff rigidity must at some points have exceeded 40%. The position of the CR equator must change as well. The results of Gall's computations are given in Fig. 6.4.



Fig. 6.4 Variation of the cutoff rigidity with geographic longitude and latitude in the epochs 1855 and 1955 for the northern hemisphere **a** and southern hemisphere **b** (According to Gall, 1960, 1962)

6.3 Trajectory Calculations of Long-Term Variation of Planetary Distribution of Cutoff Rigidities

6.3.1 Results for 1600–2000 by Steps of 50 Years

Shea and Smart (1977, 1990, 1997) have shown that in the present era the geomagnetic cutoff rigidities are rapidly changing in several areas of the world with increases on the order of 1% per year in the North Atlantic Ocean area and decreases >0.5% per year in the South Atlantic Ocean area. They show that these changes are nonlinear in time and for precise CR intensity measurements, the geomagnetic cutoff rigidities must be calculated using a field model appropriate for the time of the measurements. The dipole and non-dipole components of the magnetic field are rapidly changing. The non-dipole terms contribute about 18% of the total magnetic field. At our current point in geological time, the earth's magnetic field is rapidly decreasing. The magnitude of the dipole term alone has changed by 39% over 400 years (from 1600 to 2000). This change is so rapid and nonuniform that the magnetic field Working Group 8 of IAGA Division V provides updates to the International Geomagnetic Reference Field every 5 years (Sabaka et al., 1997). These changes affect the geomagnetic cutoff rigidities and hence the magnitude of the cosmic radiation incident on the atmosphere at a specific location is a function of time. There has been considerable interest in constructing models of the earth's magnetic field in the past (Merrill et al., 1997). Through various international research efforts, models of the earth's magnetic field extending back centuries (Barraclough, 1974, 1978) and even millennia in time (Constable et al., 2000) have been derived, although with decreasing confidence in the model's accuracy.

Smart and Shea (2003) and Shea and Smart (2004) have calculated a world grid of CR geomagnetic cutoff rigidities in the vertical direction every 50 years to establish the long-term changes in the geomagnetic cutoff rigidities during 1600–2000. They have utilized the International Geomagnetic Reference Field Models for these calculations for epochs between 2000 and 1900 and the British Geological Survey models (restricted to degree of order 5) for epochs between 1850 and 1600. The CR trajectory-tracing method (see the detailed description in Chapter 3) was used to determine the geomagnetic cutoff rigidity parameters for a set of world grids every 5° in latitude and 15° in longitude. In Figs. 6.5–6.13 these results are shown (in GV) for the years 1600–2000 in steps of 50 years.

From Figs. 6.5–6.13 a big change in cutoff rigidity planetary distribution can be seen. For example, in 1600 the highest vertical cutoff rigidity values were over South America, whereas in 2000 the highest vertical cutoff rigidity values were close to India. This is consistent with the migration of the north geomagnetic polar axis from over Northern Europe to over North America: the position of the eccentric dipole from the center of the earth changed at the rate of 0.8 km per year from 1650 to 1800 increasing to a rate of 0.9 km per year from 1800 to the present (the north dipole axis position had a steady movement of 0.11 degree per year westward and 0.03 degree southward per year from 1650 to 1850; after 1850 the southward drift became very small).

6.3.2 An Example of Cutoff Variability on CR Station LARC During 1955–1995 in Connection with Geomagnetic "Jerks"

In Storini et al. (1999) vertical cutoff rigidities were computed for the Antarctic Laboratory for Cosmic Rays (LARC station with geographic coordinates: 62.20°S,



Fig. 6.5 Vertical CR cutoff rigidity contours for 1600 (From Smart and Shea, 2003)



Fig. 6.6 Vertical CR cutoff rigidity contours for 1650 (From Smart and Shea, 2003)

301.04°E; altitude 40 m a.s.l.) using the Definitive Geomagnetic Reference Field for 1955–1990 and the International Geomagnetic Reference Field for 1995. Long-term rigidity changes were evaluated in 5-year increments. A steady decrease in LARC cutoffs was found over this 40-year period, with clear evidence of the change in the secular variation of the magnetic field that has its origin inside the earth (e.g., geomagnetic "jerks").

The LARC station is operating with a 6-NM-64 detector on King George Island (see a description of LARC in Cordaro and Storini, 1992). A preliminary evaluation of the vertical cutoff rigidities for charged particles reaching the LARC location



Fig. 6.7 Vertical CR cutoff rigidity contours for 1700 (From Smart and Shea, 2003)



Fig. 6.8 Vertical CR cutoff rigidity contours for 1750 (From Smart and Shea, 2003)

were made for the geomagnetic epochs 1980.0 and 1990.0 in Storini et al. (1995). In addition to the cutoff values determined using the International Geomagnetic Reference Field (IGRF) appropriate for the epoch 1995.0 (IGRF-95), Storini et al. (1999) also used the Definitive Geomagnetic Reference Field (DGRF) models to determine vertical cutoff rigidity values every 5 years from 1955 (DGRF-55) through 1990 (DGRF-90).

As a first step of these calculations, the Geomagnetic Field Synthesis Program (version 3.0) made available by NOAA Web pages was run for the period



Fig. 6.9 Vertical CR cutoff rigidity contours for 1800 (From Smart and Shea, 2003)



Fig. 6.10 Vertical CR cutoff rigidity contours for 1850 (From Smart and Shea, 2003)

1955.0–2000.0 using 1-year increments. Figure 6.14 shows the strength of the magnetic field and its components at LARC for this interval.

The evolving field at the LARC location is clearly evident in Fig. 6.14. To evaluate its long-term effects on charged-particle access at the LARC station, a quiescent geomagnetic field model without the inclusion of external currents on the magnetosphere was used. Storini et al. (1999) started trajectory calculations at the top of the atmosphere (assumed to be 20 km) and, working backward and traced an antiproton out through the field. This corresponds to the trajectory of a proton coming from the interplanetary medium through the magnetosphere hitting the atmosphere at 20



Fig. 6.11 Vertical CR cutoff rigidity contours for 1900 (From Smart and Shea, 2003)



Fig. 6.12 Vertical CR cutoff rigidity contours for 1950 (From Smart and Shea, 2003)

km above the station site and then creating a nuclear cascade to the detection location on the earth's surface. Calculations for particle access from the vertical direction were made for particles having rigidities between 20.00 GV and 0.02 GV. The following rigidity intervals were used: 1 GV intervals between 20.00 and 10.00 GV; 0.10 GV intervals between 9.30 and 6.30 GV, 0.05 GV intervals between 6.25 and 5.40 GV, and 0.01 GV intervals for the remaining lower rigidities. Figure 6.15 illustrates the results of these calculations where allowed particle rigidities are shown as dark areas and forbidden particle rigidities are shown by white areas.

As expected from the decreasing geomagnetic components shown in Fig. 6.14, there is a decreasing trend in the LARC cutoffs. The linear fit of the upper rigidity



Fig. 6.13 Vertical CR cutoff rigidity contours for 2000 (From Smart and Shea, 2003)



cutoffs (R_U , first allowed/forbidden pair) shown by the solid circles in Fig. 6.16 suggests a steady change in R_U about -0.02 GV per year.

An overall similar decrease is evident in the effective cutoff rigidity (R_C , solid squares in Fig. 6.16). However, in this case the slope is not uniform throughout the 40-year period. While R_U decreases nearly steadily from 1965 to 1995, the R_C

Fig. 6.15 Penumbra function for CR access at LARC location. Allowed trajectories are shown as dark areas and the forbidden ones by white areas (From Storini et al., 1999)





values oscillate somewhat around the decreasing trend. This oscillation is much more prominent in the values of R_L , the lower cutoff rigidity, shown as solid triangles in Fig. 6.16. The CR penumbra, defined as the region between the first allowed/forbidden pair of trajectories (in rigidity space) and the last allowed/forbidden pair, is generally chaotic in nature. Moreover, most of the allowed particles in the penumbra region are associated with trajectories that traverse large longitudinal ranges in transit between outer space and their arrival at a specific location at the top of the atmosphere. While it was noted as apparent discontinuities in the R_L values at 10-year intervals (i.e., 1970, 1980, 1990), these discontinuities may be a consequence of geomagnetic effects and/or the sampling procedure through the CR penumbral region.

The study of the long-term variability of the geomagnetic field has revealed the existence of rapid changes or "jerks" in the slope of the curve of the annual secular variation (e.g., Sabaka et al., 1997 and references therein). These "jerks" behave as step functions in the rate of secular change. Previous studies indicate the occurrence of three worldwide jerks during the second half of the 20th century: in 1969, 1978, and 1991. However, the intensity of the "jerks" is not only different with respect to the components of the magnetic field at any specific location, but also the occurrence may not be concurrent throughout the world. Geomagnetic data from many locations must be evaluated to determine if the observed changes are local or part of a worldwide perturbation in the earth's magnetic field. Recently, De Michelis et al. (1998) analyzed the "jerks" in 1969, 1978, and 1991, and derived the time interval in which each jerk should have occurred. Figure 6.17 shows the annual Y-component for the geomagnetic field at the LARC location and the difference for successive years where $Y' = (Y_i - Y_{i-1})$ for i = 1960 to 2000.

The horizontal lines in the lower part of Fig. 6.17 show the time of each worldwide "jerk." The dotted lines illustrate the changes in the Y component at the LARC location coinciding with the worldwide magnetic "jerks." However, the Y' trend presents other changes, even more prominent than those associated with the



Fig. 6.17 Long-term variation of the Y component of the geomagnetic field and its derivative (Y') at LARC location. The time occurrence of 1969, 1978, and 1991 worldwide geomagnetic "jerks" ($\mathbf{J}^{69}, \mathbf{J}^{78}, \mathbf{J}^{91}$) is shown (see the text for details). Arrows indicate the corresponding Y' changes at LARC location (From Storini et al., 1999)

worldwide geomagnetic "jerks." These would be local variations related perhaps with the South American geomagnetic anomalies and should only affect CR trajectories during their final path to their arrival at the top of the atmosphere above the station's location. It is possible that the worldwide geomagnetic "jerks" might explain some of the variability in the CR penumbral structure over a long period of time. This must be confirmed by yearly rigidity studies for several geographic locations. If these worldwide geomagnetic discontinuities appreciably affect the trajectories of CR particles, it would primarily be for those lower rigidity particles that encircle the earth with very long complicated paths. This effect would not be evident for near-equatorial locations where the penumbra is extremely small or, in most cases, does not exist.

Storini et al. (1999) note that while the overall lowering of the vertical cutoff rigidity at the LARC location coincides with a decrease in the geomagnetic field components at the same location, deviations from a smooth decrease have been identified. These deviations tend to coincide within the time intervals of the worldwide geomagnetic "jerks" which is believed to arise from short-term (when compared with secular changes) internal variations of the earth's core. Additional studies are necessary to ascertain if (1) the changes in cutoff rigidity values can be isolated to time periods smaller than 5-year intervals, and (2) if similar cutoff rigidity changes are present at comparable geomagnetic locations around the world.

6.3.3 Long-Term Variations of the Planetary Distribution of Geomagnetic Rigidity Cutoffs During the Last 2,000 Years

Using trajectory calculations of CR in the geomagnetic field, Kudela and Bobik (2004) determined the changes of CR vertical cutoff rigidities' planetary distribution during the last 2,000 years. The computations were done for cutoff rigidities at the earth's surface using the IGRF model data for 1900–2000 and information on the geomagnetic field in the past from different sources. The contour maps of vertical cutoff rigidities using a set of 10 Gauss coefficients for the period of years between 0 and 1600 are obtained. Kudela and Bobik (2004) also estimated the trends in long-term variability of CR rigidity cutoffs at different positions on the earth's surface.

The geomagnetic field had significant variability in the past. Although there are many papers dealing with the changes of the geomagnetic field over long periods in the past (e.g., Quidelleur et al., 1994; McElhinny and Senanayake, 1982), information basically concentrated on the dipolar strength which is not enough for the precise determination of the cutoff rigidities. The problem is how to obtain exact knowledge on the geomagnetic field in the past. Hongre et al. 1998) analyzed the field over the past 2,000 years and derived a model up to degree n = 2 plus the degree n = 3 of order m = 3 Gauss coefficients (g33 and h33) for the period 0–1700 with a time step of 25 years. Bloxham and Jackson (1992) used the last 300 years to produce two time-dependent field maps for 1690–1840 and 1840–1990. The global geomagnetic field models for the past 3,000 years are described by

Constable et al. (2000). For the period of 1900–2000, the IGRF coefficients up to order/degree 10 are available (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html). The IGRF models for the main field are truncated at n = 10 (120 coefficients). During the 20th century, the geomagnetic field was strongly changing. Xu Wen-yao (2000) indicate that while the dipole moment of the geomagnetic field has decreased by 6.5% since 1900, the strengths of its quadruple and octuple components have increased by 95% and 74%, respectively. The magnetic center has shifted 200 km toward the Pacific. The IGRF field had some specific features at higher-degree coefficients (Xu Wen-yao, 2000). During 1945–1955, the coefficients g_n^m and h_n^m with n > 7 show unusual jumps not observed before and after.

Many authors have discussed the long-term variability of the geomagnetic cutoffs. Bhattacharyya and Mitra (1997) derived an analytical expression for the cutoff rigidity of CR arriving at a point from an arbitrary direction using the main geomagnetic field approximation as that of an eccentric dipole. They used the expression derived to determine changes in geomagnetic cutoffs due to secular variation of the geomagnetic field since 1835. Flückiger et al. (2003) discussed the differences in computations of the cutoffs using the trajectory technique in the model dipolar field and the GEANT technique for the past 2,000 years (for details, see Section 6.5). Smart and Shea (2003), and Shea and Smart (2004) calculated a detailed world grid of vertical geomagnetic cutoff rigidities with a time step of 50 years from 1600 until 2000 (see Section 6.3.1). They used the IGRF models for the epochs 2000, 1950, and 1900. For the years between 1600 and 1850 they used the British Geological Survey geomagnetic model restricted to degree of order 5.

For the trajectory computations in the model field Kudela and Bobik (2004) used a method similar to earlier ones (e.g., Shea et al., 1965), tracing the CR particle trajectory from a given point on the earth's surface with a reversed charge sign and velocity vector and numerically solving the equation of motion in the model field B. The details of the computation method and dependence of the result on parameters of computations are described in papers by Bobik et al. (2003a, b) and Kudela and Bobik (2004). For the field B over a long time period, Kudela and Bobik (2004) used the modified Geopack 2003 subroutines (http://nssdc.gsfc.nasa.gov/ space/model/magnetos/data-based/modeling.html) based on the IGRF geomagnetic field model (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html). The cutoffs (R_L, $R_{\rm C}$, $R_{\rm U}$ defined by Cooke et al., 1991) are computed for the vertical direction of incidence. Earlier comparison of the results of our method of computation of vertical cutoffs with those by Shea and Smart (2001) was made only for one middle- and one high-latitude station, and small differences were found (Kudela and Bobik, 2004). Trajectory computations of Kudela and Bobik (2004) cover the years from 0 to 2000 A.D. They use 10 Gauss coefficients g10, g11, h11, g20, g21, g22, h21, h22, g33, and h33 collected from Hongre et al. (1998) for the years 0-1700 and the full set of IGRF model's Gauss coefficients for 1900-2000. The period 1700-1900 is covered by g10, g11, and h11 (Bloxham and Jackson, 1992).

To compare obtained results with those published earlier, Kudela and Bobik (2004) calculated the vertical cutoff rigidities in a dipole field approximation (i.e., using only g10, g11 and h11 Gauss coefficients) for two epochs, namely 1600

	-							
Lat.	Long. (E)	Epoch 2000	Epoch 1900	Epoch 1800	Epoch 1700	Epoch 1600	Change in GCR flux (1600–1900)	
55	30	2.30	2.84	2.31	1.49	1.31	-48%	Europe
50	0	3.36	2.94	2.01	1.33	1.81	-37%	Europe
50	15	3.52	3.83	2.85	1.69	1.76	-55%	Europe
40	15	7.22	7.62	5.86	3.98	3.97	-58%	Europe
45	285	1.45	1.20	1.52	2.36	4.14	+214%	N. America
40	255	2.55	3.18	4.08	4.88	5.89	+118%	N. America
20	255	8.67	12.02	14.11	15.05	16.85	+68%	N. America
20	300	10.01	7.36	9.24	12.31	15.41	+195%	N. America
50	105	4.25	4.65	5.08	5.79	8.60	+132%	Asia
40	120	9.25	9.48	10.24	11.28	13.88	+76%	Asia
35	135	11.79	11.68	12.40	13.13	14.39	+37%	Japan
-25	150	8.56	9.75	10.41	11.54	11.35	+25%	Australia
-35	15	4.40	5.93	8.41	11.29	12.19	+178%	S. Africa
-35	300	8.94	12.07	13.09	10.84	8.10	-63%	S. America

Table 6.1 Vertical cutoff rigidities (in GV) for various epochs 1600–2000, and galactic CR intensity variation during 1600–1900 owed to changes of geomagnetic field (According to Shea and Smart, 2003)

and 1900. The vertical cutoff rigidities were also calculated in the model field described by 10 Gauss coefficients (hereafter n = 2+). In the dipolar approach, the most remarkable increases of cutoffs were found for 1600-1900 westward of South America and in the center of the Asian continent, while decreases were found in Central America and westward of Australia. A similarity with the pattern obtained earlier (see Table 6.1 and Fig. 6.24 in Section 6.4 from the paper by Shea and Smart, 2003) was found in Kudela and Bobik (2004) computations. A difference of the picture when using only a dipole and using the n = 2+ approximation was also found. Using n = 2+ yields a more complicated structure of spatial changes of cutoff over the globe (three regions of local extremes both in the Southern and Northern Hemispheres). Using selected points on the Earth's surface with most remarkable changes of the CR flux between 1600 and 2000 according to Shea and Smart (2003), it was found small differences of Kudela and Bobik (2004) computations with those obtained in the Shea and Smart (2003) for selected periods (see below Table 6.1 in Section 6.4). While for n = 10 the computed rigidities are similar to those obtained in the Shea and Smart (2003) paper (for 1900 and 2000), differences from using only the dipolar field and n = 2 + coefficients are found. However, the trend and the temporal variability is similar using the n = 2+ approximation for the interval 1600–2000 to that with higher precision (n = 5) used in Shea and Smart (2003).

Kudela and Bobik (2004) estimated the influence of the degree (*n*) used in the computations of particle trajectories and the consequences for the vertical estimated cutoffs. The calculation for n = 1, 2, ... 10 was made for selected positions. The computations of cutoff rigidities for a central European position, for a position near the equator, and for a position in the southern hemisphere have shown that the cutoff rigidity is stable starting above n = 4. To understand the error in the estimate of

vertical cutoffs at different places on the earth's surface when using only n = 2+ with respect to the more precise one (n = 10), Kudela and Bobik (2004) constructed maps of the differences between cutoffs obtained by the two approximations for the grid (30° longitude $\times 10^{\circ}$ latitude) for 1900 and 2000. The difference is shown in Fig. 6.18.

To understand the long-term changes of the vertical cutoffs at different positions over the globe during the past 2,000 years, the computations were made with n = 2+. The temporal step is 100 years. The grid is constructed with $15^{\circ} \times 10^{\circ}$ (longitude × latitude) steps. The long-term evolution of the vertical cutoffs at four different longitudes is shown in Fig. 6.19.

A variety of different long-term variations of cutoffs at different positions on the earth's surface is apparent from the selection. For example, while for the longitude 30 E the cutoff is decreasing from years 400 to 1000 at 30°N, the opposite trend is seen for the same latitude in the south. The opposite change in cutoff temporal profile is also seen at 300°E longitude for latitude 30° in the two hemispheres during the period 1500–1700.

The contour maps of vertical cutoffs with the time step 100 years were constructed from the grid. The selection is shown in Fig. 6.20.

For the period from 1900 to 2000 the full set of Gauss coefficients was used from the IGRF model (n = 10) for the computations on the grid and for the construction of contour maps of vertical cutoff rigidities. The lines of constant changes of $R_{\rm C}$ are plotted in Fig. 6.21.

The most remarkable decrease of the cutoff is apparent in the southern Atlantic and in the southern part of South America. Contrary to that, the cutoffs are not changing significantly in central Europe. The long-term change of the L parameter, which can be used for the estimation of the cutoff values (Shea et al., 1987) was found also not to be changing significantly in central Europe, but is strongly increasing in the southern hemisphere at LARC yielding in cutoff decrease (Kudela and Storini, 2001).

It was found that *L* values for LARC (62.20° S, 301.04° E) and Lomnicky Štit (LŠ, 49.20° N, 20.22° E) during 1945–2000 were changing very differently, while in 1945 the *L* value at both stations was approximately the same (≈ 2.05), in 2000 *L* at LŠ remained almost the same, but at LARC it increased to ≈ 2.25 .

Kudela and Bobik (2004), on the basis of estimated vertical cutoff rigidities in the past, determined by trajectory computations of CR particles in the model geomagnetic field up to n = 2+, came to following conclusions:

- 1. The method gives similar results for 1900 and 2000 to those of Shea and Smart (2003); vertical cutoff rigidities converge to a stable value for $n \ge 4$ for the epoch when the IGRF is available.
- 2. The maximum cutoff rigidity decreased from $\approx 24 \text{ GV}$ around year 0 to $\approx 17 \text{ GV}$ for the epoch 2000; the place of maximum cutoff changes with time.
- 3. There have been a variety of time profiles of cutoff rigidity at different sites on the earth during the past 2,000 years; these local peculiarities should be taken into account in the study of relations between CR and climate changes as well as in the analysis of cosmogenic nuclides.



Fig. 6.18 The planetary distribution of differences between vertical cutoffs (in GV) computed with n = 2+ and n = 10. Lines of constant $R_C(n = 10) - R_C(n = 2+)$ for IGRF 1900 (*upper panel*) and 2000 (*bottom panel*) are plotted. Positive and negative values are marked by solid and dotted lines (From Kudela and Bobik, 2004)


Fig. 6.19 Long-term changes of effective vertical cutoffs at the longitudes 30° , 120° , 210° , and 300° for the northern and southern hemispheres at different latitudes. Splines smoothing is used (1800 is not computed) (From Kudela and Bobik, 2004)



Fig. 6.20 Contour maps of vertical cutoff rigidities estimated from the computations using the approximation n = 2+ in years 0, 400, 800, 1200, 1600 (Coefficients from Hongre et al., 1998) and for year 2000 using n = 2+ selection from IGRF model (From Kudela and Bobik, 2004)

6.3.4 On the Variation of the Earth's Magnetic Dipole Moment During 1600–2005

Smart and Shea (2007) determined the variation of the earth's magnetic dipole moment during 1600–2005. Results are shown in Fig. 6.22.

6.3.5 Long-Term Variation of the Planetary Distribution of the Geomagnetic Rigidity Cutoffs Between 1950 and 2000

Smart and Shea (2007) determined the long-term variation of the planetary distribution of the geomagnetic rigidity cutoffs between 1950 and 2000 (see Fig. 6.23).



Fig. 6.21 Contour maps of the changes in vertical cutoff rigidity values (in GV) during the past century (*top panel*) and during its second half (*bottom panel*). The IGRF model with n = 10 was used (From Kudela and Bobik, 2004)



Fig. 6.22 Change in value of the earth's dipole as represented by the Gauss coefficient G(1,0). On the ordinate axes are shown the magnitude of dipole field at the equator in nT (From Smart and Shea, 2007)



Fig. 6.23 A map of the change in vertical cutoff rigidity (in units of GV) between 1950 and 2000 (black indicates increase, grey indicates decrease) (From Smart and Shea, 2007)

6.4 Long-Term Change of Cutoff Rigidities and the Expected Change of CR Intensity Owed to Geomagnetic Field Variation

The intensity of cosmic radiation reaching the top of the atmosphere is a function of the earth's geomagnetic field. While the total field is decreasing, the changes are non-uniform over the earth. Shea and Smart (2003) show that the CR intensity impinging at the top of the atmosphere has shown a considerable amount of variation from place to place over the past 400 years.

On the basis of the results discussed in Section 6.3.1, Shea and Smart (2003) calculated the expected long-term change of cutoff rigidities during 1600–1900. The results are shown in Fig. 6.24. From Fig. 6.24 it can be seen that on the earth there are several regions with big negative and positive changes of CR cutoff rigidities (up to 7 GV). The vertical cutoff rigidity values and changes in the galactic cosmic radiation calculated by Shea and Smart (2003) are shown in Table 6.1 which reflect major changes at individual locations over a 300-year period. These changes are not uniform. There are also locations (e.g., 55 N, 30 E; 20 N, 300 E; 35 S, 300 E) where the 300-year trend reverses between 1900 and 2000.

The total strength of the earth's magnetic dipole decreased significantly between 1600 and the present time. Smart and Shea (2003) estimated a globally averaged increase in the CR flux of $\sim 18\%$ over this 400-year period.



Fig. 6.24 Contours of the change in vertical cutoff rigidity values (in GV) between 1600 and 1900. Full lines reflect positive trend (increasing of cutoff rigidity from 1600 to 1900); dotted lines reflect negative trend (From Shea and Smart, 2003)

6.5 The Global Cutoff Rigidities and their Change During the Last 2,000 Years

Flückiger et al. (2003) investigated the evaluation of global CR cutoff rigidities for the past 2,000 years. The state-of-the-art technique for the determination of cutoff rigidities is the calculation of particle trajectories in a magnetic field model representing the earth's magnetic field at a specific time. For a specified location (geographic latitude λ and longitude φ), and a specified arrival direction (zenith angle θ , azimuth angle ϕ), allowed and forbidden trajectories are determined by numerically integrating the equation of motion of charged particles as a function of particle rigidity. The effective cutoff rigidity $R_{c,eff}(\lambda, \varphi, \theta, \phi)$ takes into account geomagnetic filtering effects in the penumbra region (see Sections 3.11–3.12). For effective cutoff rigidities not only vertically arrived particles but also those arrived at different zenith angles are important. At a specific location, the global cutoff rigidity

$$R_{\rm c,gl}(\theta_{\rm max},\lambda,\phi) = \frac{\int\limits_{0}^{2\pi} d\phi \int\limits_{0}^{\theta_{\rm max}} R_{\rm c,eff}(\theta,\phi) \sin\theta d\theta}{2\pi \int\limits_{0}^{\theta_{\rm max}} R_{\rm c,eff}(\theta,\phi) \sin\theta d\theta}.$$
(6.4)

is a valuable parameter describing the lower rigidity limit of CR particles arriving at this location. During the past 2,000 years, the magnetic dipole moment of the earth decreased by \sim 30% to today's value of \sim 7.8 × 10²⁵ Gs cm⁻³, and the location of the north geomagnetic pole has changed within a limited latitudinal range near the geographic pole (Merrill and McElhinny, 1983).

Examples of contour lines of 2π -averaged global cutoff rigidities at $\theta_{max} = 85^{\circ}$ are plotted in Fig. A6.1 for global magnetic cutoff rigidities determined by Eq. 6.4 for the geocentric dipole field model with dipole moments 11.7×10^{25} Gs cm³ (2,000 years ago) and 7.8×10^{25} Gs cm⁻³ (present time). A comparison of two panels in Fig. A6.1 shows that 2,000 years ago the contour lines for 15 GV were at higher latitudes (on 5–15°) in both hemispheres than in the present time. It is in accordance with the results, described Section 6.3.2, obtained by Kudela and Bobik (2004) that 2,000 years ago the maximum CR cutoff rigidity for the vertical direction on the earth was 24 GV in comparison with 19 GV at the present time.

Figure A6.2 is the same as in Fig. A6.1, but represents the eccentric dipole field model with dipole moments 11.7×10^{25} Gs cm⁻³ (2,000 years ago) and 7.8×10^{25} Gs cm⁻³ (present time). For the corresponding calculations, the information about the position and direction of the magnetic dipole inside the earth was deduced from the IGRF.

In Fig. A6.3 the contour lines $R_{c,gl}(\theta_{max},\lambda,\varphi) = 2 \text{ GV}$ for $\theta_{max} = 85^{\circ}$ in the northern and southern hemispheres are shown for geocentric and eccentric dipole field models (geomagnetic dipole moment $7.8 \times 10^{15} \text{ Vcm}^{-1}$, present time). The total area enclosed by the solid contours (geocentric dipole) in the north and south corresponds to ~15% of the earth's surface. With the eccentric dipole instead of the

geocentric dipole, the surface inside the 2 GV contour line is reduced in the north by \sim 7% and enlarged in the south by \sim 6%. In particular, as illustrated in Fig. A6.3, the use of the geocentric instead of the eccentric dipole field model may lead to considerable differences between the northern and southern hemispheres (Flückiger et al., 2003).

6.6 Effects of Axially Symmetric Currents in the Magnetosphere: The Provisional Assessment of the Causes of Variations in Cutoff Rigidities During Magnetic Storms

6.6.1 Development of Models of the Axially Symmetric Current's Influence on CR Cutoff Rigidities

The first to draw attention to the possibility of variations of the geomagnetic cutoff rigidity was Chapman (1937). He suggested that when the strength of the magnetic field at the earth's surface is reduced during the main phase of a magnetic storm, the field outside the equatorial ring current is, at the same time, strengthened and that, as a whole, the magnetic moment of the earth during that period is increased. This should be accompanied by an increase of the geomagnetic threshold and by a corresponding reduction of CR intensity at the earth's surface. Chapman thought to explain in this way the Forbush effect, i.e., the decrease of CR intensity at the time of magnetic storms. However, Johnson (1938) showed that Chapman's assumption would be valid only if the equatorial ring current would be formed very close to the earth's surface. If the ring current is formed sufficiently far away, say, at some earth's radii, the region of space inside the ring, where the strength of the magnetic field is reduced, has a dominating influence. Hayakawa et al. (1960) showed that the influences of the two parts of space should cancel out if the ring current has 1.3 times the radius of the earth. Treiman (1953, 1954) confirmed this value of the radius and computed the expected variation of the cutoff rigidity of the particles for various latitudes and different values of the radii of the ring current. Numerous investigations of the field of the perturbations during worldwide magnetic storms show that the radius of the ring current must at least be several times the radius of the earth (see in detail Vol. 2). Hence, contrary to the suggestion in Chapman (1937), during magnetic storms some decrease of the cutoff rigidity should be expected and a corresponding increase of CR intensity. The considerable decrease which is actually observed - the so-called Forbush effect - is a phenomenon of quite different character connected with the magnetic fields frozen into the corpuscular streams in the interplanetary plasma. It is not easy to distinguish the effect of a ring current against the background of a considerable Forbush effect. Only the observations in the program of the IGY made a fair separation of these effects possible, but the theoretical understanding is still incomplete.

The first to consider the motion of a charged particle in the combined field of dipole and ring current in the equatorial plane was Störmer (1911, 1912). Later Ray (1956a) studied the influence of such a ring current on the latitude effect of the primary cosmic radiation in the 11-year solar cycle and concluded that variation of the parameters of the ring current changes the threshold rigidity, which again causes the "knee" of the latitude effect to shift in latitude. It is easily seen that this explanation generally gives the wrong sign for the 11-year CR variation. Evidently, one of the main causes of the decrease of cutoff during magnetic storms is the actual strengthening of the ring current in western direction in the radiation belts. However, this mechanism is not sufficient. Thus, Akasofu and Lin (1963) computed the magnetic moment $M_{\rm rc}$ of a ring current for a given distribution of density and pitch angles of the radiation trapped in the belts. They estimated for CR incident at high latitudes that

$$\overline{R}_{\rm c}/R_{\rm c} = (1 + M_{\rm rc}/M_{\rm E})^{-1},$$
 (6.5)

where \overline{R}_{c} and R_{c} are the cutoff rigidities with and without ring current and M_{E} is the magnetic moment of the earth. Data about the radiation belts show that \overline{R}_{c}/R_{c} can vary only from 0.5 to 1. But observations, even during a moderate magnetic storm, give $\overline{R}_c/R_c \sim 0.06$. Therefore Akasofu and Lin (1963) assume that there must exist yet another mechanism causing particles of very low energy to reach the earth during magnetic storms at high latitudes $>65^{\circ}$. Webber (1963) believes that besides the ring current, a homogeneous field in the magnetosphere must be assumed, parallel to the dipole axis and formed by current systems at the boundary between the earth's magnetosphere and the interplanetary medium. In order to explain the large decrease of the rigidity and the fact that the cutoff is not sharp, Ray (1964) assumes that the geomagnetic field is confined because it is made turbulent by the solar wind at large distances from the earth. He estimates a ring current, with a magnetic moment of 0.45, as that of the earth. Thus, in computing the rigidity variations during magnetic storms it should be taken into account that the geomagnetic field is confined by the flux of solar plasma. But even in the absence of corpuscular streams, the earth is lying in the solar wind, with a velocity of $\sim 300 \text{ km/s}$ relative to the earth. Thus a cavity is formed free from moving plasma. From the relation

$$H^2/8\pi \approx nmu^2,\tag{6.6}$$

where magnetic field of the earth

$$H \approx 2H_o \left(r_{\rm E}/r \right)^3,\tag{6.7}$$

and *n* is the density of the solar wind, *u* its velocity, *m* the mass of the proton, H_o is the magnetic field strength at the surface, we find for the radius r_c of the cavity

$$r_{\rm c} \approx \left(H_o^2/2\pi nmu^2\right)^{1/6} \approx 10r_{\rm E} \tag{6.8}$$

assuming $n \sim 5 \text{ cm}^{-3}$ and $u \sim 3 \times 10^7 \text{ cm/s}$. Thus, even in the undisturbed state, the cutoff rigidity, especially at high latitudes, must be somewhat smaller than for the





dipole. When the earth is in a solar corpuscular stream $u \sim 10^8$ cm/s, r_c decreases to a few earth's radii. Estimates by Rothwell (1959) showed that the largest variation of the geomagnetic threshold should occur at high latitudes and that large variations of the dimensions of the cavity must lead to considerable changes of the geomagnetic threshold, a decrease of these dimensions corresponding to a decreased threshold and an increased CR intensity (see Fig. 6.25).

As known, during magnetic storms the strength of the field increases somewhat, but later, in the main phase, a strong decrease occurs caused by the strengthening of the ring current in the outer radiation belt. The perturbed geomagnetic field can at that time be approximated by the sum of a dipole field and a homogeneous field, the entire geomagnetic field being restricted to a cavity with radius r_c , outside which the field is strongly irregular and distorted, so that the outer part of the field may be neglected. Representing the disturbed field of the earth in this simple form, Obayashi (1959) finds the rigidity variations at various latitudes as a function of the dimensions of the cavity and the changes of the *H*-component of the earth's field during a magnetic storm, which is shown in Fig. 6.26.

From Fig. 6.26 it can be seen that the variation of the cutoff rigidity is not proportional to ΔH and that the maximum of this variation occurs for different values of R_c , depending on ΔH . Obayashi's result has the form:

$$\overline{R}_{c}(\Delta H) = R_{c} \left[1 + \frac{r_{E}^{3} \Delta H}{M_{E}} \left(4 \cos^{-6} \lambda - 1 \right) \right], \tag{6.9}$$

where $\overline{R}_c(\Delta H)$ and R_c are the cutoff rigidity for vertically incident particles in a perturbed field and in the dipole field, respectively, r_E and M_E are radius and magnetic moment of the earth, ΔH is the variation of the *H*-component of the geomagnetic field at the equator, and λ is the geomagnetic latitude. Solomon (1966) has generalized this result to the case of particles obliquely incident in the east–west plane:



Fig. 6.26 Expected change ΔR_c of cutoff rigidity R_c during magnetic storm, as a function of the change in the *H*-component of the field; the numbers with the curves are ΔH at the equator in nT (According to Obayashi, 1959)

$$\overline{R}_{c}(\Delta H, \omega) = R_{c}(\omega) \left[1 + \left(\frac{1+k}{k}\right) \frac{r_{E}^{3} \Delta H}{2M_{E}} \left((1+k)^{2} \cos^{-6} \lambda - 1 \right) \right], \quad (6.10)$$

where ω is the angle with the east–west line and

$$k \equiv \left(1 - \cos\omega \cos^3 \lambda\right)^{1/2}.$$
 (6.11)

For vertically incident particles ($\omega = \pi/2$) Eq. 6.10 reduces to Eq. 6.9. This simple model is valid for geomagnetic latitudes λ , satisfying the condition

$$\cos^6 \lambda \gg 10^{-5} \times (\Delta H/0.63), \qquad (6.12)$$

where ΔH is in Gs. For example, for $\Delta H = 63 \,\text{nT} = 63 \times 10^{-5} \,\text{Gs}$, the maximum geomagnetic latitude for which this model is valid will be $\lambda \approx 70^{\circ}$.

6.6.2 The CR Vertical Cutoff Rigidities in the Presence of a Thin Equatorial Ring Current

Calculations of the vertical cutoff rigidity were first made by Sauer (1963) under various assumptions about the radius and magnetic moment of the equatorial ring current. Table A6.1 shows the results for all CR stations of the IGY network above 45° latitude. Here $M_{\rm E} = 8.1 \times 10^{25} \,\rm Gs \, cm^{-3}$ is the magnetic moment of the earth and $r_{\rm E} = 6.4 \times 10^8 \,\rm cm$ is the radius of the earth. Column 4 is the cutoff rigidity undisturbed by a ring current with, for comparison, in columns 2 and 3 the corresponding numbers from Störmer and from the dipole approximation. In columns

5–10 in the first row the top numbers are ratios r_c/r_E , and bottom numbers are ratios M_c/M_E , where r_c and M_c are radius and magnetic moment of the ring current, correspondingly.

6.6.3 The CR Cutoff Rigidities for Obliquely Incident Particles in the Presence of a Thin Equatorial Ring Current

Under the same assumptions as in Sauer (1963), Dorman and Tyasto (1965a) presented an analytical expression for the cutoff rigidity for obliquely incident particles. As an example of the solution of such problems, we shall derive this result in some detail. The equation of motion of a charged particle with charge Ze, mass m and velocity v in the magnetic field H is

$$\dot{\mathbf{v}} = \frac{Ze}{mc} \left[\mathbf{v} \times \mathbf{H} \right],\tag{6.13}$$

where the dot indicates, as usual, differentiation with respect to time. Put $\mathbf{H} = \text{rot}\mathbf{A}$, where A is the magnetic vector potential. If A does not depend on time, the velocity v and mass m of the particle $m = m_o (1 - v^2/c^2)^{-1/2}$ remain constant and the differentiation with respect to time may be replaced by differentiation with respect to the line element ds = vdt.

Then, if the magnetic vector potential is symmetric with respect to the *z*-axis, the ϕ -component of Eq. 6.13 in spherical coordinates has the first integral:

$$r^{2}\frac{\mathrm{d}\varphi}{\mathrm{d}s} + \frac{A_{\varphi}}{R}r\cos\lambda = 2\gamma, \qquad (6.14)$$

where R = mvc/Ze is the rigidity of the particle, A_{φ} is the φ -component of the vector potential (the other components of *A* are zero), 2γ is an integration constant with the dimension of a length and proportional to the impact parameter of the particle. If the angle between the velocity vector and the meridian plane is called θ , Eq. 6.14 may be written as

$$\sin\theta = \frac{2\gamma}{r\cos\lambda} - \frac{A_{\varphi}}{R}.$$
(6.15)

The combined magnetic field of the dipole and the thin ring current of radius r_c , in the equatorial plane, has

$$A_{\varphi} = \frac{M_{\rm E} \cos \lambda}{r^2} + \frac{2M_{\rm c}}{\pi r_{\rm c}} \frac{F(x)}{\left(r_{\rm c} r \cos \lambda\right)^{1/2}},\tag{6.16}$$

where

$$M_{\rm E} = 8.1 \times 10^{25} \,\,{\rm Gs.cm}^3, \,\,M_{\rm c} = \pi r_{\rm c}^2 I/c,$$
 (6.17)

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and I is the current in electrostatic units. In Eq. 6.16

$$x^{2} = \frac{4r_{c}r\cos\lambda}{r^{2} + 2r_{c}r\cos\lambda + r_{c}^{2}}$$
(6.18)

and

$$F(x) = \frac{2}{x} (K(x) - E(x)) - xK(x), \qquad (6.19)$$

where K(x) and E(x) are complete elliptical integrals of type I and II defined by

$$K(x) = \int_{0}^{\pi/2} (1 - x^{2} \sin \omega)^{-1/2} d\omega, \quad E(x) = \int_{0}^{\pi/2} (1 - x^{2} \sin \omega)^{1/2} d\omega. \quad (6.20)$$

Substitution of Eq. 6.16 into Eq. 6.15 gives

$$\sin\theta = \frac{2\gamma}{r\cos\lambda} - \frac{M_{\rm E}}{R} \left[\frac{\cos\lambda}{r^2} + \frac{2M_{\rm c}}{M_{\rm E}} \frac{F(x)}{\pi r_{\rm c}^{3/2} (r\cos\lambda)^{1/2}} \right].$$
 (6.21)

Let us introduce Störmer's unit of length $S = (M_E/R)^{1/2}$. Expressing *r* and γ in units *S*, we obtain

$$\sin\theta = \frac{2\gamma}{r\cos\lambda} - \frac{\cos\lambda}{r^2} - \frac{2M_c}{M_E} \frac{F(x)}{\pi r_c^{3/2} (r\cos\lambda)^{1/2}}.$$
 (6.22)

Since $\sin \theta$ cannot be larger than one, Eq. 6.22 gives the condition for the division of space into forbidden and permitted regions. The form of these regions depends on the value of the integration constant γ . If γ lies outside the range $\gamma_1 - \gamma_2$, the inner permitted region near the origin is completely separated from the outer permitted region, which extends to infinity. Particles moving from infinity cannot then reach the surface of the earth. If γ lies between γ_1 and γ_2 , the inner and outer allowed regions are connected with each other and particles with rigidity higher than a minimum value can reach the earth. The critical values r_{cr} and γ_{cr} are determined from a system of two equations (in the equatorial plane)

$$|\sin\theta| = 1, \ \partial \sin\theta / \partial r = 0. \tag{6.23}$$

After some algebra transformations and introducing a new variable $\rho = r_c/r_{cr}$, we obtain the system of equations which was used for computing r_{cr} and γ_{cr} :

$$\rho^{2} - \frac{M_{c}}{\pi M_{e}} \left[\frac{K(x)}{\rho + 1} - \frac{E(x)}{\rho - 1} \right] = r_{c}^{2}, \qquad (6.24)$$

$$\gamma_{\rm cr} = \frac{\rho}{r_{\rm c}} \left[1 + \frac{M_{\rm c}}{2\pi M_{\rm E}} \left(\frac{K(x)}{\rho + 1} - \frac{E(x)}{\rho - 1} \right) \right]. \tag{6.25}$$

Here

$$x = 4u(u+1)^{-2}.$$
 (6.26)

The roots u_{cr} of Eq. 6.24 for given M_c/M_E and r_c , substituted into Eq. 6.25 give γ_{cr} as a function of r_c^2 . Further, with the critical values of γ_{cr} in Eq. 6.22 for $r = r_E$, we may compute the threshold rigidities for various azimuth and zenith angles ϕ and ζ :

$$\sin\theta = \sin\zeta\cos\phi. \tag{6.27}$$

Figures 6.27–6.35 give the rigidities computed in Dorman and Tyasto (1965a) for $M_c/M_E = 0.5$, 0.75, and 1.0 and $r_c/r_E = 3, 5$, and 9 for the zenith angles at steps 15° in the east–west plane.

From Figs. 6.27–6.35 it can be seen that with a decreasing radius of the ring current or with an increasing current in the ring, the threshold rigidities decrease for



Fig. 6.27 Polar diagram showing the cutoff rigidity R_c for all directions of incidence in the eastwest plane. The panel represents the following assumption about the ring current: $M_c/M_E = 1$, $r_c/r_E = 3$. Different curves refer to different geomagnetic latitudes λ (According to Dorman and Tyasto, 1965a)



Fig. 6.28 The same as in Fig. 6.27, but for $M_c/M_E = 2$, $r_c/r_E = 5$ (According to Dorman and Tyasto, 1965a)



Fig. 6.29 The same as in Fig. 6.27, but for $M_c/M_E = 2$, $r_c/r_E = 9$ (According to Dorman and Tyasto, 1965a)



Fig. 6.30 The same as in Fig. 6.27, but for $M_c/M_E = 1.5$, $r_c/r_E = 5$ (According to Dorman and Tyasto, 1965a)



Fig. 6.31 The same as in Fig. 6.27, but for $M_c/M_E = 1.5$, $r_c/r_E = 9$ (According to Dorman and Tyasto, 1965a)



Fig. 6.32 The same as in Fig. 6.27, but for $M_c/M_E = 2$, $r_c/r_E = 3$ (According to Dorman and Tyasto, 1965a)



Fig. 6.33 The same as in Fig. 6.27, but for $M_c/M_E = 1$, $r_c/r_E = 5$ (According to Dorman and Tyasto, 1965a)



Fig. 6.34 The same as in Fig. 6.27, but for $M_c/M_E = 1$, $r_c/r_E = 9$ (According to Dorman and Tyasto, 1965a)



Fig. 6.35 The same as in Fig. 6.27, but for $M_c/M_E = 1.5$, $r_c/r_E = 3$ (According to Dorman and Tyasto, 1965a)





western as well as for eastern directions. The reduction of the equatorial field at the earth's surface, ΔH , caused by the ring current is shown in Fig. 6.36.

In computing the influence of the ring currents of the magnetosphere on CRs during magnetic storms, the tables of the E_i indices computed by Kertz (1964) for the IGY, may be useful. The index E_i is given at 3-h intervals of the Greenwich day and corresponds to the field of the ring current at the equator; E_i is numerically equal to the deviation of the H-component at a low-latitude observatory from its constant value. In order to exclude the field of the Sq variations, the values H have been taken for the nocturnal hours only. The quantities ΔH can be reduced to the geomagnetic equator by simple geometric formulae. The values of E_i during the IGY were computed from data of 27 observations at different longitudes.

6.7 Influence of Current Sheets Surfaces on the CR Geomagnetic Cutoff Rigidities

6.7.1 Current Sheet in the Form of a Spherical Surface

The effect of a western current in the form of a spherical surface was considered by Treiman (1953, 1954). A more accurate solution was found by Dorman and Tyasto (1964, 1965b), who considered the influence of a westward current along parallels on the sphere, with a strength proportional to the cosine of the latitude. This model of the current during the main phase of a magnetic storm was first proposed by Chapman (1937). The vector potential of a current on the surface of a sphere with radius r_c and with effective moment M_c is determined, in the case of axial symmetry with respect to the *oz*-axis, by the expression

$$A_{\rm cr} = 0, A_{\rm c\theta} = 0, A_{\rm c\phi} = \begin{cases} M_{\rm c} r \cos \lambda / r_{\rm c}^3 & \text{if} \quad r \le r_{\rm c} \\ M_{\rm c} \cos \lambda / r^2, & \text{if} \quad r \ge r_{\rm c} \end{cases}$$
(6.28)

Since the vector potential of the total field is

$$A_{\rm r} = 0, \ A_{\theta} = 0, \ A_{\varphi} = (M_{\rm E}/r^2) \cos \lambda + A_{\rm c}\varphi,$$
 (6.29)

we find by Eq. 6.28 (expressing all lengths in Störmer units):

$$\sin \theta = \begin{cases} \frac{2\gamma_1}{r\cos\lambda} - \frac{\cos\lambda}{r^2} - \frac{M_c}{M_E} \frac{r\cos\lambda}{r_c^3}, & \text{if } r \le r_c, \\ \frac{2\gamma_2}{r\cos\lambda} - \left(1 + \frac{M_c}{M_E}\right) \frac{\cos\lambda}{r^2}, & \text{if } r \ge r_c. \end{cases}$$
(6.30)

The solution of the system of Eq. 6.30 for $r_{\rm cr} \ge r_{\rm c}$ is

$$\gamma_{2\rm cr}^2 = 1 + \frac{M_{\rm c}}{M_{\rm E}}; \quad r_{2\rm cr} = \gamma_{2\rm cr}^{-1},$$
 (6.31)

and for $r_{\rm cr} \leq r_{\rm c}$

$$2\gamma_{\rm lcr} = \frac{3\left(r_{\rm cr}^2 + 1\right)}{r_{\rm cr}}; \quad r_{\rm cr}^3 - \frac{r_{\rm c}^3\left(r_{\rm c}^2 + 1\right)}{2M_{\rm c}/M_{\rm E}} = 0.$$
(6.32)

The rigidities for vertically incident particles, computed for a decrease of the horizontal component of the geomagnetic field at the equator $\Delta H = 2M_c/r_E^3$, by 100, 200, 300 and 400 nT, are shown in Fig. 6.37.

The corresponding ratios M_c/M_E are shown in Table 6.2.

From Fig. 6.37 it can be seen that at low latitudes, the rigidity decrease at a certain value of ΔH is practically independent of the quantity r_c/r_E , while at latitudes above 40°, it increases considerably with decreasing r_c/r_E .



Fig. 6.37 Threshold rigidities as a function of geomagnetic latitude for four values of $\Delta H = 100$, 200, 300, and 400 nT. The dependence on $r_c / r_E =$ shows up only at high latitudes. Dotted curve: pure dipole (From Dorman et al., 1965b)

6.7.2 Current Sheet Formed by Rotating the Line of Force of the Magnetic Dipole

Dorman et al. (1965a) have investigated the influence on cosmic particle rigidity of currents distributed on a sheet formed by rotating a line of force of the magnetic

$\Delta H, nT$	$r_{\rm c}$ / $r_{\rm E}$		
	3	5	9
100	0.0437	0.202	1.180
200	0.0875	0.405	2.359
300	0.131	0.607	3.539
400	0.175	0.810	4.718

Table 6.2 The ratios M_c/M_E for the various assumptions made in Fig. 6.37

dipole around its axis. This form was chosen for the following reasons. At present one cannot state categorically that the currents in the radiation belt are identical with the currents responsible for the main phase of a magnetic storm. However, the motion of the particles producing the currents in the main phase of the magnetic storm is probably of the same character as that of the particles of the radiation belts. The form of the currents causing the decrease of the horizontal component during a magnetic storm as well as that of the currents in the radiation belt, should be related to the lines of force of the magnetic field, for it is known that the motion of a particle trapped by this field is composed of rotation around a line of force, oscillation between the reflection points, and a longitude drift along the magnetic envelope (for details see Chapter 6). Currents in the radiation belts can therefore be represented as flowing over the surface of the magnetic envelope. The magnetic effects produced at the surface of the earth by such a model current were computed by Ben'kova and Tyurmina (1962); the results for various assumptions about the character of the variation of the current density along the line of force was compared with the latitude distribution of the D_{st} -variation from data of the worldwide net of magnetic observatories. The best agreement between computed and observed values of the H-component of the geomagnetic field is obtained for a current density increasing toward the polar zone as

$$J = J_o \left(1 + C_1 \cos^2 \psi \right), \tag{6.33}$$

and a radius of the ring $r_c = 9r_E$ (see Fig. 6.38). Here C_1 is a constant, ψ is the latitude angle counted from the southern end of the polar axis, and r_E is the radius of the earth.

The entire surface may be divided into separate elementary ring currents of infinitely small width dl, with their centers on the *z*-axis. At the point of observation $M(r, \lambda)$ (where *r* is the modulus of the radius vector, λ the geomagnetic latitude for the centered dipole), the elementary ring current of width dl gives a magnetic field with the vector potential

$$dA_2 = \frac{2d\mu F(x)}{\pi b \left(br\cos\lambda\right)^{1/2}}; \quad d\mu = \pi b^2 J/dl, \tag{6.34}$$

where the current density J is measured in CGSE units. Here $d\mu$ is the effective magnetic moment of the elementary ring current dl. The function F(x) in Eq. 6.34 is



Fig. 6.38 Geometry of the current sheet formed by rotating a magnetic line force (From Dorman et al., 1965a)

determined by the complete elliptical integrals K(x) and E(x) according to Eq. 6.20, but

$$x^{2} = \frac{4b\varepsilon}{(b+\varepsilon)^{2} + (z-h)^{2}}.$$
(6.35)

Here *b* is the radius of the elementary current; *J* its density; *h* the elevation above the equator plane of the elementary current dl, and ε the distance of the point of observation from the dipole axis. Hence the equation of the ring current being formed can be written as the equation of a dipole line of force

$$\rho = r_{\rm c} \sin^2 \psi, \tag{6.36}$$

where r_c is the value of ρ in the equatorial plane. The current surface touches the earth at latitude $\psi = \alpha$ and $\psi = \pi - \alpha$. Taking into account Eq. 6.36, we find by means of Fig. 6.38 and from geometric considerations that

$$b = r_{\rm c} \sin^3 \psi, h = -r_{\rm c} \sin^2 \psi \cos \psi, dl = r_{\rm c} \sin \psi \sqrt{1 + 3\cos^2 \psi} d\psi.$$
(6.37)

Substituting Eq. 6.37 in Eq. 6.34, we find

$$d\mu = \pi J r_c^3 \sin^7 \psi \sqrt{1 + 3\cos^2 \psi} d\psi.$$
(6.38)

Substituting Eq. 6.37 and Eq. 6.38 into Eq. 6.35 and considering that $\varepsilon = r \cos \lambda, z = r \sin \lambda$, we obtain

$$x^{2} = \frac{4r_{c}r\cos\lambda\sin^{3}\psi}{\left(r\cos\lambda + r_{c}\sin^{3}\psi\right)^{2} + \left(r\sin\lambda + r_{c}\sin^{2}\psi\cos\psi\right)^{2}}.$$
(6.39)

Substitution of Eq. 6.38 and the expression $b = r_c \sin^3 \psi$ in Eq. 6.34 gives the vector potential of the magnetic field due to the elementary current:

$$dA_2 = \frac{2r_c^{3/2}J\sin^{5/2}\psi}{(r\cos\lambda)^{1/2}}\sqrt{1+3\cos^2\psi}F(x)d\psi.$$
 (6.40)

In order to find the corresponding expression for the entire current sheet, we must integrate Eq. 6.40 along the whole length of the line of force from point A to point B on the earth's surface (see Fig. 6.38), i.e. from $\psi = \alpha$ to $\psi = \pi - \alpha$. In the general case, the current strength depends on ψ . Then the vector potential of the entire current envelope will be

$$A_{2} = \frac{2r_{\rm c}^{3/2}}{(r\cos\lambda)^{1/2}} \int_{\alpha}^{\pi-\alpha} J\sin^{5/2}\psi\sqrt{1+3\cos^{2}\psi}F(x)\,\mathrm{d}\psi.$$
(6.41)

The combined field of the current sheet and the magnetic dipole $M_{\rm E}$ at the origin, will be

$$A = \frac{M_{\rm E}}{r^2} \cos \lambda - A_2. \tag{6.42}$$

The vector potential A does not depend on longitude ω . Therefore, for a charged particle moving in such an axially symmetric field, Störmer's first integral of motion (Eq. 6.15) is valid.

Substituting Eq. 6.43 into Eq. 6.15 and expressing *r* and *J* in Störmer units $S^2 = M_E/R$, we obtain

$$\sin\theta = \frac{2\gamma}{r\cos\lambda} - \frac{\cos\lambda}{r^2} - \frac{2r_{\rm c}^{3/2}S^3}{M_{\rm E}(r\cos\lambda)^{1/2}} \int_{\alpha}^{\pi-\alpha} J\sin^{5/2}\psi\sqrt{1+3\cos^2\psi}F(x)\,\mathrm{d}\psi$$
(6.43)

Equation 6.43 gives the division of space in permitted and forbidden regions. A particle can move in places where $|\sin \theta| < 1$ (permitted region), and is not allowed to enter the region of space where $|\sin \theta| > 1$. From $|\sin \theta| = 1$, we find the equation of the curve in the meridian plane separating the permitted from the forbidden regions.

Again, if γ is larger than a certain critical value γ_{cr} , the inner permitted region, near the earth, and the outer one are separated by a forbidden region, and particles cannot reach the earth from infinity. For $\gamma < \gamma_{cr}$, the two permitted regions are connected and particles may move toward the earth unhindered. For $\gamma = \gamma_{cr}$ the two allowed regions are flowing together in a point in the meridian plane at distance $r = r_{cr}$ (the "passage" point). The critical distances of the passage points r_{cr} and the critical values of the impact parameter γ_{cr} for which particles with corresponding rigidity can reach the earth, are found from the system of equations, analogous to considered in Section 6.6 (see the system from two equations, Eq. 6.23):

$$\frac{1}{r_{\rm cr}^2} - \frac{\beta}{\sqrt{r_{\rm cr}}} \int_{\alpha}^{\pi-\alpha} J \sin^{5/2} \psi \sqrt{1 + 3\cos^2 \psi} \left[\frac{1}{2} F(x) + r_{\rm cr} \frac{\partial F(x)}{\partial r_{\rm cr}} \right] \mathrm{d}\psi = 1, \quad (6.44)$$

$$r_{\rm cr} + \frac{1}{r_{\rm cr}} + \beta \sqrt{r_{\rm cr}} \int_{\alpha}^{\pi-\alpha} J \sin^{5/2} \psi \sqrt{1 + 3\cos^2 \psi} F(x) \,\mathrm{d}\psi = 2\gamma_{\rm cr}, \tag{6.45}$$

where

$$\beta = 2r_{\rm c}^{3/2} S^{3/2} S^3 / M_{\rm e}, \tag{6.46}$$

and x^2 is for $\lambda = 0$ equal to

$$x^{2} = 4r_{c}r_{cr}\sin^{3}\psi \left[\left(r_{cr} + r_{c}\sin^{3}\psi \right)^{2} + \left(r_{c}\sin^{2}\psi\cos\psi \right)^{2} \right]^{-1}.$$
 (6.47)

The derivative in Eq. 6.39 is

$$\frac{\partial F(x)}{\partial r_{\rm cr}} = \frac{1}{x} \left[\frac{2 - x^2}{2(1 - x^2)} E(x) - K(x) \right] \frac{r_{\rm c}^4 \sin^4 \psi - r_{\rm cr}^2}{r_{\rm cr} \left(r_{\rm cr}^2 + 2r_{\rm c} r_{\rm cr} \sin^3 \psi + r_{\rm c}^2 \sin^2 \psi \right)}.$$
 (6.48)

Substituting Eq. 6.48 into Eq. 6.39 and with the new variable $u = r_{cr}/r_c$, we have, instead of Eqs. 6.39 and 6.40 following equations

$$\frac{1}{r_{\rm c}u^2} - \frac{r_{\rm c}S^3}{M_{\rm e}} \sqrt{u} \int_{\alpha}^{\pi-\alpha} J \sqrt{\frac{1+3\cos^2\psi}{\sin\psi}} \times \\ \times \left[K(x) - \frac{u^2 + \sin^4\psi(1-2\sin^2\psi)}{u^2 - 2u\sin^3\psi + \sin^4\psi} E(x) \right] \mathrm{d}\psi = 1,$$
(6.49)
$$r_{\rm c}u + \frac{1}{r_{\rm c}u} + \beta \sqrt{r_{\rm c}u} \int_{\alpha}^{\pi-\alpha} J \sin^{5/2}\psi \sqrt{1+3\cos^2\psi} F(x) \,\mathrm{d}\psi = 2\gamma_{\rm cr}.$$
(6.50)

For given values of r_c , J, and M_E , u may be found from Eq. 6.49 and with these values of u in Eq. 6.50 γ_{cr} can be determined as a function of S and finally as a function of the cutoff rigidity R, because S and R are connected by the formula $S^2 = M_E/R$. We adopt from Ben'kova and Tyurmina (1962) two different expressions for J (in CGSE units):

$$J = 4.8 \times 10^{-5} \left(1 + 0.5 \cos^2 \Psi \right), \tag{6.51}$$

$$J = 8.2 \times 10^{-5} \left(1 + \cos^2 \Psi \right). \tag{6.52}$$

Actually, neither measurements made on the earth nor those of the magnetic field in space on rockets and satellites can decide unambiguously which place of the currents causes the decrease of the *H*-component of the magnetic field at the earth's surface. Radii of the current rings between 3 and $10r_E$ have been found by various methods (see Ben'kova and Tyurmina, 1962; and the review in Dolginov and



Fig. 6.39 Dependence of the difference $\Delta R_c = R_{cd} - R_c$, where R_c is the computed rigidity, on the latitude for the values of *J* defined by Eq. 6.51 (*left* panel) and Eq. 6.52 (*right* panel) for $r_c / r_E = 5$, 7.5, 9, 10 (curves 1, 2, 3, 4, respectively, r_E is the radius of the earth) (From Dorman et al., 1965a)

Pushkov, 1963). Therefore we have made the computations for $r_c/r_E = 5$; 7.5; 9, and 10. Figure 6.39 shows the difference $\Delta R_c = R_{cd} - R_c$ between the cutoff rigidity in a dipole field R_{cd} and the computed rigidity R_c as a function of latitude.

Figure 6.39 shows that the cutoff rigidity for any given current strength decreases most rapidly at intermediate latitudes. The magnitude of the effect increases with increasing radius of the current sheet, but this simply arises because with increasing radius, for a given current density, the total current increases on account of the increased area.

6.8 The Effect of Volume Currents in the Radiation Belts (Akasofu and Chapman Model) on the CR Cutoff Rigidity

By the method described in Section 6.7, the effect of an arbitrary axially symmetric three-dimensional current system on the cutoff rigidity can be computed. It suffices to write down an expression of the type Eq. 6.42 for the vector potential and to perform an additional integration over r_c , taking into account the volume distribution of the current. The further procedure is exactly as explained above. Such a problem was solved by Dorman et al., (1966) for the current system corresponding to the motion of trapped particles in the model of the radiation belts by Akasofu and Chapman (1961). Skipping the rather cumbersome computations we immediately give the result. For the particular current system found in Akasofu and Chapman (1961), which gives a perturbation $\Delta H = 50 \text{ nT}$ at the earth's surface, the change in rigidity expected according to Dorman et al. (1966) during the main phase of a magnetic storm is found to be too large: the neutron intensity should increase by 17.5% and 12.5% at geomagnetic latitudes 20° and 30° , respectively. This result strongly contradicts CR observations, since the increase observed for such a relatively small perturbation has a considerably smaller amplitude (see Section 6.14). Thus, CR data can yield additional information about the correctness of the hypotheses about the structure of current systems in radiation belts.

6.9 The Influence of Ring Currents on the Position of CR Impact Zones and Asymptotic Directions

An interesting study of the influence of a ring current on the position of the 9-h impact zone of solar particles was made in dipole approximation by Ray (1956b), who computed 55 trajectories of vertically incident particles, with rigidities 2, 6, and 10 GV. Since the φ -component of the vector potential of the field due to the equatorial ring current, can be written as

$$A_{\varphi} = \begin{cases} M_{\rm c} r \cos \lambda / r_{\rm c}^3, & \text{for } r < r_{\rm c}, \\ M_{\rm c} \cos \lambda / r^2, & \text{for } r > r_{\rm c}, \end{cases}$$
(6.53)

where M_c is the dipole moment of the ring (in units of the earth's dipole moment); r_c is the radius of the ring (earth's radius as unit); r is distance from the centre of the earth (in Störmer units), the equation of motion of a particle in the cylindrical coordinate system ρ , φ , and z (measured in Störmer units, with $r^2 = \rho^2 + z^2$) is:

$$\frac{\mathrm{d}^2\rho}{\mathrm{d}s^2} = \rho \frac{\mathrm{d}\varphi}{\mathrm{d}s} \left(\frac{4\gamma}{R^2} - \frac{3b\rho^2}{r^5} - \frac{\mathrm{d}\varphi}{\mathrm{d}s}\right), \ \frac{\mathrm{d}^2z}{\mathrm{d}s^2} = -z\frac{3b\rho^2}{r^2}\frac{\mathrm{d}\varphi}{\mathrm{d}s}, \ \frac{\mathrm{d}\varphi}{\mathrm{d}s} = \frac{2\gamma}{\rho^2} - \frac{b}{r^3} - D.$$
(6.54)

Here γ is an integration constant, *s* is the path length of the particle (in Störmer units), and the parameters *b* and *D* are determined by

$$b = 1$$
, $D = M_c/r_c^3$ for $r < r_c$; $b = M_c + 1$, $D = 0$ for $r > r_c$. (6.55)

The results, obtained by numerical integration of Eq. 6.54, for vertical incidence in the combined dipole field and field of an equatorial ring current, are given in Table A6.2. Comparison of Table A6.2 with computations for a dipole field without ring current shows that the ring current leads to a shift in longitude of $10-15^{\circ}$ of the impact zones. A realistic assessment of the effect of an equatorial ring current on the trajectories of particles in the geomagnetic field requires that higher harmonics of this field are taken into account, and also that data about the ring current obtained with the aid of rockets and satellites are used. We now know (e.g., Dolginov and Pushkov, 1960; Sonett et al., 1960; Shevnin, 1961) that the ring current actually exists and lies at a distance of 7-10 earth's radii. McCracken (1962), using from data of Sonett et al. (1960), computed the asymptotic angles A (latitude at infinity) and Ψ (longitude at infinity) for particles arriving along the vertical at Churchill, taking into account the real magnetic field of the earth and the ring current. The results for two values of rigidity are given in Table 6.3. For comparison, the data obtained without the ring current are also given. This table confirms the first results of Ray (1956b), discussed above, that the ring current displaces the impact zones over angles $\leq 15^{\circ}$.

Rigidity, GV	Angle	Equatorial ring current		
		Not counted	Counted	
1.45	Λ	0.7°	8.9°	
	Ψ	-68.5°	-80.8°	
1.88	Λ	5.8°	11.8°	
	Ψ	-70.8°	-80.9°	

 Table 6.3 The asymptotic directions for the station Churchill with and without the ring current being taken into account (According to McCracken, 1962)

6.10 Effect of Compression of the Magnetosphere (Current System in Eastern Direction) on CR Cutoff Rigidities

Besides the current system of western direction discussed in Sections 6.5–6.9 (present in the main phase of a magnetic storm), a current system of eastern direction also occurs, causing a shrinking of the earth's magnetosphere according to Eq. 6.8. In the first approximation, this current system may be thought to have axial symmetry, and therefore we apply the integral described by Eq. 6.15 to determine the cutoff rigidities. Since the real current system leads to rather complicated functions of the space coordinates r and λ , for simplicity a simpler model is considered in which a current density proportional to $\cos \lambda$ (Obayashi, 1959; Kellogg and Winckler, 1961) flows over the surface of a sphere with radius $r_{\rm m}$. The vector potential then is

$$A = \begin{cases} [M_{\rm c} \times r]/r^3, & \text{if } r > r_{\rm m}, \\ [M_{\rm c} \times r]/r_{\rm m}^3, & \text{if } r < r_{\rm m}. \end{cases}$$
(6.56)

This means that the field inside the sphere is homogeneous, while outside it is a dipole field. The cutoff rigidity for the field described by Eq. 6.56 was determined by Obayashi, 1959 (see Section 6.6). However, as shown by Asaulenko et al. (1965), the field of the homogeneous compression of the magnetosphere by the plasma of the solar wind (e.g., theoretical analysis by Zhigulev, 1959a, b; Midgley and Davis, 1962; Spreiter and Hyett, 1963; experimental results in Dolginov and Pushkov, 1963) differs from that found from Eq. 6.56 by about 15%. Therefore, the variations of the cutoff rigidity by compression of the magnetosphere were computed by Asaulenko et al. (1965) with a more realistic model of Midgley and Davis (1962), both without a current system in the western direction ($M_c = 0$) and with such a current system. Figure 6.40 shows the computed variations of the vertical cutoff rigidity R_c in comparison with the cutoff rigidity in a dipole field. Here r_m is the radius of the magnetosphere.

Comparison with Obayashi (1959) shows that the difference in R_c with the model of a spherical magnetosphere is about 10%. The curves which include a western ring current have a discontinuity corresponding to the passage of the transition point to



Fig. 6.40 Changes in vertical cutoff rigidity R_c arising from compression of the magnetosphere. Left panel: actual rigidities versus latitude in the presence of a ring current (*below*) and without a ring current (*above*). Right panel: same numbers in the form of percentage differences from dipole cutoff rigidities (According to Asaulenko et al., 1965)

the outside of the ring current, which is infinitely thin in this approximation. Upon approaching the polar regions, the transition points move outward toward the boundary of the magnetosphere, where the field is asymmetric and Störmer's Eq. 6.15 cannot be applied. Only for particles with low rigidity whose motions can be described by the equation in drift approximation, can Eq. 6.15 be applied in the asymmetric field, too. This has been done by Akasofu (1963) for an asymmetric confined field, formed by a combination of the dipole field with ring current and a dipole field which is the mirror image of the first. Application of Störmer's integral in this case for the noon meridian gives good agreement with experimental data at high latitudes. At other latitudes, R_c is found to be considerably larger than expected for a dipole field, in sharp contrast to experiment (see Section 6.14.8).

6.11 Effect of Compression of the Magnetosphere and Western Current Systems on CR Asymptotic Directions and the Acceptance Cones

In order to assess the influence of the limited extension of the earth's magnetic field on the position of the impact zones, one must compute at least a few CR trajectories in such a field. In Asaulenko et al. (1965) and Smirnov (1965), the fourth-order RungetKutta method was applied for obtaining the trajectories of vertically incident particles in a perturbed field. The integration was stopped when a negatively charged particle reached the boundary of the cavity and the velocity vector at that point was taken to have the asymptotic direction. The steps were chosen small enough to keep errors below 0.1°. Table A6.3 gives the asymptotic longitude Ψ and latitude Λ (in geomagnetic coordinates) for a pure dipole field and for compression of the magnetosphere with radii of the cavity $r_{\rm m} = 8$, 10, and 12 earth radii. The computations were made for geomagnetic latitudes 50° and 60° . As seen from Table A6.3, if the geomagnetic field is compressed, the asymptotic velocity vector turns to the east, i.e., the angles Ψ become larger, contrary to the influence of the ring current on CR trajectories, when the asymptotic velocity vector turns to the west and, hence, the angles Ψ decrease (in accordance with that obtained by Ray, 1956b). Near the cutoff rigidity, the asymptotic velocity vector is turned over a considerably larger angle of more than 100°. Above, the cutoff rigidities were shown to also increase if the geomagnetic field is compressed. In summary, we see that compression of the field leads both in the cutoff rigidity and in the asymptotic directions to a stronger effect of the geomagnetic field on CR. The combined influence of the finite dimension of the magnetosphere and of the western ring current on the impact zones was studied by computing 40 trajectories in such a combined field. The same approximation was applied as earlier and the magnetic moment and radius of the western current again were $M_c = 1M_E$ and $r_c = 5r_E$. The results for latitudes $\lambda = 50^\circ$ and 60° are in Table A6.4. The western currents in the magnetosphere are seen to compensate part of the effect of the finite dimension of the magnetosphere. The influence on the effective asymptotic directions Ψ (bearing angle) and Λ (the asymptotic latitude) is seen in Table 6.4, which refers to the sample problem of observing solar CR with spectrum $\propto R^{-5}$ at geomagnetic latitude 60° .

Angles	Dipole	$r_{\rm m} = 12r_{\rm E}$ $M_{\rm c} = 0$	$r_{\rm m} = 10r_{\rm E}$ $M_{\rm c} = 0$	$r_{\rm m} = 8r_{\rm E}$ $r_{\rm c} = 5r_{\rm E}$ $M_{\rm c} = M_{\rm E}$	$r_{\rm m} = 12r_{\rm E}$ $r_{\rm c} = 5r_{\rm E}$ $M_{\rm c} = M_{\rm E}$
Ψ	62.6°	93.0°	107.0°	69.8°	55.6°
Λ	-14.2°	-16.3°	-15.3°	-4.3°	6.6°

Table 6.4 Average asymptotic directions for a sample rigidity spectrum $\propto R^{-5}$ under the combined influence of finite magnetosphere size and a ring current at geomagnetic latitude 60°

6.12 Asymmetric Variations of the Magnetosphere and Diurnal CR Variations of Geomagnetic Origin

Elliot (1963) performed interesting terrella experiments to study the asymmetric variation of the geomagnetic cutoff rigidity. Figure 6.41 shows the expected relative rigidity variation as a function of local time at various latitudes for the simultaneous influence of a dipole field and a homogeneous field of strength 50 gammas, perpendicular to the dipole axis. Figure 6.42 gives, for a uniform field of 50 nT, the expected amplitudes of the daily variations at various geomagnetic latitudes. The variation of the geomagnetic cutoff rigidity, expected if there is an eccentric ring current with moment $0.1M_{\rm E}$ in the equatorial plane, is given in Fig. 6.43. Possible perturbations of the diurnal CR variation at low latitudes, due to an eccentric ring current, have been studied by Cummings (1966). Makino and Kondo (1965) numerically computed trajectories of vertically incident particles, for directions 0, 6, 12, and 18 h local time and geomagnetic latitudes 0°, 30°, 40° and 50°. The field of the earth was taken as that of a centered dipole with moment $8.06 \times 10^{25} \, {\rm Gs \, cm^{-3}}$, and that of the asymmetric cavity, with a boundary at $9r_{\rm E}$ in the direction of the sun, was taken from Mead (1964) with spherical harmonic coefficients:

$$G_1^0 = -0.277, \quad G_2^0 = 0.108, \quad G_3^0 = -0.112, \quad G_4^0 = 0.024.$$
 (6.57)

The resulting penumbra, described by the function f(R) (zero for forbidden and 1 for allowed regions) is shown in Fig. 6.44 for the dipole without and with cavity.

Table 6.5 gives the effective rigidities R_c in GV expected according to the formula

$$\int_{R_{\rm c}}^{\infty} \mathrm{d}R = \int_{0}^{\infty} f(R) \,\mathrm{d}R. \tag{6.58}$$

The asymmetric variation of the cutoff rigidities must lead to a solar-daily variation of local origin. The expected amplitude and phase, computed by means of the coupling coefficients, are shown in Table 6.6.

Figure 6.45 compares the expected diurnal variations of local origin with those observed during the IGY for the neutron component at sea level.

It is seen from Fig. 6.45 that the magnetospheric effects and observed variations are of the same order of magnitude, so that the influence of the asymmetric cavity on the observed diurnal variations must be important. The tail of the magnetosphere cannot sensibly change the results of Makino and Kondo (1965), since this lies beyond 10 earth's radii and influences particles of much lower rigidity only.

6.13 Oscillation of the Asymptotic Acceptance Cones

The earth's magnetic field, as deformed by the solar wind, also affects the asymptotic directions of incidence; for the stations Chacaltaya, Deep River, and London this has been studied by Ahluwalia and McCracken (1965, 1966). The computations



Fig. 6.41 Variation in geomagnetic cutoff rigidity with local time, which would result from the superposition of a uniform field of 50 gammas perpendicular to the dipole axis. Panel **a**: At geomagnetic latitude $25^{\circ} N \pm 1^{\circ}$, the time of minimum R_c (maximum of CR intensity) is $t_{\min} = 07.30$ h, and the amplitude of solar-day variation of R_c is A = 0.32%; **b**: $40^{\circ} N \pm l^{\circ}$, $t_{\min} = 15.30$ h, A = 0.74%; **c**: $48^{\circ} N \pm l^{\circ}$, $t_{\min} = 11.00$ h, A = 2%; **d**: $53^{\circ} N \pm l^{\circ}$, $t_{\min} = 10.30$ h, A = 3.4% (According to Elliot, 1963)

were made at intervals of 3 h local time and for various values of $r_{\rm ms}$, which is the distance from the center of the earth to the magnetopause in the direction of the sun measured in earth's radii. Table 6.7 gives as an example the asymptotic directions



Fig. 6.42 The CR daily variation to be expected from the cutoff rigidity variation of Fig. 6.41 (According to Elliot, 1963)



Fig. 6.43 Variation in cutoff rigidity produced by an eccentric ring current of moment $0.1 M_{\rm E}$ (According to Elliot, 1963)

for a neutron monitor at Chacaltaya. The displacement of the asymptotic direction for a dipole field without magnetopause is 21.4° .

The asymmetric magnetopause is seen to result in a diurnal motion of the asymptotic cone. A sinusoidal anisotropy of the CRs in interplanetary space with amplitude 0.4% and directed 90° west of the line earth–sun, would by this diurnal motion



Fig. 6.44 Results of trajectory computations in the dipole field with and without the cavity. Black areas are the forbidden regions and blank spaces indicate the allowed regions. Arrows show the effective cutoff rigidities R_c (According to Makino and Kondo, 1965)

Model	Direction	Geomagnetic latitude			
		0°	30°	40°	50°
Dipole only		14.880 ± 0.0004	9.461 ± 0.036	5.370 ± 0.007	2.688 ± 0.007
Dipole + cavity	0 h 6 h 12 h 18h Mean	$\begin{array}{c} 14.991 \pm 0.0007 \\ 14.939 \pm 0.0007 \\ 14.939 \pm 0.0007 \\ 14.933 \pm 0.0007 \\ 14.933 \pm 0.0007 \\ 14.936 \pm 0.0004 \end{array}$	$\begin{array}{c} 9.744 \pm 0.010 \\ 9.744 \pm 0.011 \\ 9.819 \pm 0.010 \\ 9.744 \pm 0.011 \\ 9.763 \pm 0.005 \end{array}$	$\begin{array}{c} 5.559 \pm 0.005 \\ 5.672 \pm 0.003 \\ 5.595 \pm 0.007 \\ 5.597 \pm 0.006 \\ 5.606 \pm 0.003 \end{array}$	$\begin{array}{c} 2.900 \pm 0.009 \\ 2.925 \pm 0.009 \\ 2.869 \pm 0.006 \\ 2.856 \pm 0.007 \\ 2.887 \pm 0.004 \end{array}$

Table 6.5 Effective cutoff rigidities R_c (in GV) for dipole field in asymmetric cavity (According to Makino and Kondo, 1965)

of the cone give rise to a semi-diurnal variation with amplitude 0.060%, 0.015%, and 0.012% for $r_{\rm ms} = 5$, 10, and 15 earth's radii, respectively. Since the most probable value is $r_{\rm ms} = 10$, the expected semi-diurnal wave is considerably smaller than observed and hence the diurnal oscillation of the acceptance cone cannot be the chief cause of the observed CR semi-diurnal variation.

Razdan and Summers (1965) investigated the changes of the direction of the asymptotic acceptance cones during geomagnetic perturbations, when the magnetic field of the earth is deformed by a stream of solar plasma. They also considered the behavior of particles with rigidity close to the geomagnetic cutoff rigidity. It was found that during perturbations, in the penumbra region, forbidden and allowed cones can interchange depending on local time, which should result in variations of low energy CRs. Asymptotic acceptance cones have been determined for dipole and

Component	Geomagnetic latitude (°)	Amplitude (%)	Time of maximum (h)
Primary	30	0.64 ± 0.12	0.0 ± 0.7
-	40	1.15 ± 0.10	19.3 ± 0.4
	50	1.54 ± 0.22	16.2 ± 0.5
Neutron, $312 \mathrm{g}\mathrm{cm}^{-2}$	30	0.41 ± 0.08	0.0 ± 0.8
	40	0.48 ± 0.05	19.6 ± 0.4
	50	0.34 ± 0.05	16.5 ± 0.6
Neutron, $680 \mathrm{g}\mathrm{cm}^{-2}$	30	0.27 ± 0.05	0.0 ± 0.8
	40	0.32 ± 0.03	19.4 ± 0.4
	50	0.20 ± 0.03	16.4 ± 0.6
Neutron, sea level	30	0.18 ± 0.02	0.0 ± 0.5
	40	0.18 ± 0.02	19.9 ± 0.4
	50	0.10 + 0.01	15.9 ± 0.6
Meson, sea level	30	0.04 ± 0.01	0.0 ± 0.8

Table 6.6 Diurnal variation caused by asymmetry in cutoff rigidities (According to Makino and
Kondo, 1965)



Fig. 6.45 Expected from cavity field effect diurnal variation in the nucleonic component intensities at mountain altitudes (solid lines) and observed average during IGY on mountain stations (broken lines) (According to Makino and Kondo, 1965)

disturbed geomagnetic field at latitudes 0° , 50° , and 70° for azimuth angles 0° , 90° , 180° , and 270° , with due account of the zenith sensitivity of neutron monitors and the coupling coefficients. The change of the direction of the asymptotic cone was

Local time (h)	rms, Earth's radii			
	5	10	15	
0	49.0°	26.7°	23.1°	
3	46.9	25.8	22.9	
6	39.7	24.0	22.4	
9	34.6	23.1	22.7	
12	31.7	22.9	22.7	
15	31.9	23.7	23.0	
18	39.2	25.2	23.5	
21	48.9	26.5	23.2	

 $\begin{tabular}{ll} \textbf{Table 6.7} \ \mbox{Eastward displacement of asymptotic directions (According to Ahluwalia and McCracken, 1965, 1966) \end{tabular}$

found to be no larger than $\sim 6^{\circ}$, and the conclusion is that a strong change of this direction can only be expected for a steep spectrum, for instance, in the case of the arrival of solar particles. In summarizing the section about the expected influence of the variable magnetosphere of the earth on CRs, it can be said that at present we can compute with sufficient accuracy the behavior of cosmic particles in the actual geomagnetic field, even if there are rather complicated current systems and an asymmetric magnetosphere. With increasing accuracy of the measurements more delicate effects will also become interesting, such as the influence of ionospheric and circumpolar current systems and the structure of the penumbra and the acceptance cone.

6.14 The First Observations of CR Variations Due to Changes in the Geomagnetic Field

Much attention was paid in the 1960s to variations connected with the direct influence of changes of the geomagnetic field on CR intensity. Though these kinds of variations had been predicted long ago (see Sections 6.6–6.13), it was experimentally discovered only after the foundation of the worldwide net of CR stations in connection with the IGY and the IQSY had been set up. In fact, these variations usually occur at the same time as CR variations of considerably larger amplitude, connected with processes in interplanetary space and it is very hard to disentangle them.

6.14.1 Unusual Increases During Magnetic Storms

The direct influence of changes in the geomagnetic field on CRs was first demonstrated by Yoshida and Wada (1959), using data from the worldwide net of stations.



Fig. 6.46 Increases of the neutron intensity connected with strong magnetic storms in February 1958 **a** and in September 1957 **b** (According to Kondo et al., 1960)

They showed that worldwide CR intensity increases were in some cases connected with magnetic storms, and not with solar flares. The planetary character excludes the possibility that these increases are the result of anomalous diurnal variations connected with storms of cosmic radiation. Kondo et al. (1960) studied in detail two important cases of such CR intensity increase. Figure 6.46 shows the variations of the neutron component at a number of stations and also the change of intensity of the horizontal component of the geomagnetic field at Kakioka, for the periods September 11–15, 1957 and February 9–13, 1958.

Evidently, the CR intensity observed with neutron monitors, at intermediate and low latitudes, increased considerably on September 13, 1957 and February 11, 1958, when the intensity of the *H*-component of the field was most strongly reduced. In establishing the intensity increase at each station, the planetary intensity decrease and abnormal diurnal variation should be excluded. In first approximation the planetary reduction is found by forming 24-h sliding averages from 2-h values of the neutron intensity after the end of the observed increase. For finding the first harmonics of



Fig. 6.47 Neutron intensity increase versus cutoff rigidity; the curves follow from the theory (see Fig. 6.49) (According to Kondo et al., 1960)

the anomalous diurnal variation the differences between the 2-h values and the 24-h sliding averages were analyzed. Then the values found were extrapolated to the periods of disturbance (6–14h on September 13, 1957 and 10–16h on February 11, 1958). The amplitudes corrected for these effects are given in Fig. 6.47.

The full-drawn curves represent the theoretical estimates of the effect expected, obtained as follows: Since the decrease of the geomagnetic field during a storm is nearly the same all over the earth, this is assumed, according to Kondo et al. (1960),

to be due to a homogeneous field of strength ΔH being added in the opposite direction to the terrestrial dipole. Hence the rigidity change can be estimated by Störmer's theory of the motion of charged particles in a dipole field. The computed rigidity decrease is found to be directly proportional to ΔH (for $0 > \Delta H > -400$ nT) and to depend on the original value of the cutoff rigidity, as shown in Fig. 6.48.

Further, using the curves for the latitude effect of the neutron component at mountain and sea level, one finds the expected effect for various ΔH (Fig. 6.49). In the cases considered $\Delta H \approx -300$ nT. It is seen in Fig. 6.48 that the computations agree reasonably well with the observations. The decrease of cutoff rigidity



Fig. 6.49 Computed increase of the neutron intensity for various ΔH (According to Kondo et al., 1960)
during magnetic storms was also observed directly. This shows that CRs actually react strongly to changes of the geomagnetic field and may be a source of valuable information about the character of these changes at large distances. Therefore, detailed investigation of the effect found is very important.

6.14.2 Application of the Method of Coupling Functions

The graphs in Fig. 6.22 from the paper by Obayashi, 1959 (see Section 6.6) permit the computation made by Dorman et al. (1961) by means of the method of coupling functions of the increase to be expected during magnetic storms for various CR components at different latitudes (Figs. 6.50–6.53).

From Figs. 6.50–6.53 it is seen that:

- 1. The amplitude of the effect should increase strongly with increasing amplitude of the main phase of the magnetic storm.
- 2. The increase in the polar zone should be absent for all components except those sensitive to low-energy particles. This effect in the polar zone can only be found in observations in the stratosphere and on satellites and only during minimum solar activity.



Fig. 6.50 Expected CR intensity increase during the main phase of a magnetic storm for ionizing component in stratosphere (altitude about 30 km, *left*) and at 10 km (*right*) (From Dorman et al., 1961)



Fig. 6.51 The same as in Fig. 6.50, but for ionizing component at 4.3 km (*left*) and neutron component at 10 km (*right*) (From Dorman et al., 1961)



Fig. 6.52 The same as in Fig. 6.50, but for neutron component at mountain level 300 mb (*left*) and at sea level (*right*) (From Dorman et al., 1961)



Fig. 6.53 The same as in Fig. 6.50, but for hard (muon) component at sea level measured by ionization chamber (*left*) and by cubic telescope (*right*) (From Dorman et al., 1961)

- 3. The largest effect in the neutron component should be observed for average values of $R_c = 4 10 \,\text{GV}$, and the effect is stronger at mountain level than at sea level. The position of the zone of maximum increase should shift from $R_c = 2.5 \,\text{GV}$ for $\Delta H = -30 \,\text{nT}$ to $R_c = 7.5 \,\text{GV}$ for $\Delta H = -500 \,\text{nT}$.
- 4. Closer to the equator the amplitude of the increase of the neutron component should again decrease considerably, e.g., for the neutron component at mountain level, if $\Delta H = -100 \,\text{nT}$ the amplitude should decrease from 2% for $R_c = 5 \,\text{GV}$ to 0.3% for $R_c = 15 \,\text{GV}$, and if $\Delta H = -50 \,\text{nT}$ from 1% for $R_c = 3 \,\text{GV}$ to 0.05% for $R_c = 15 \,\text{GV}$. For large ΔH the relative change of the amplitude upon approaching the equator is somewhat smaller. Thus, if $\Delta H = -500 \,\text{nT}$ the amplitude changes from 9.5% for $R_c = 7.5 \,\text{GV}$ to 5% for $R_c = 15 \,\text{GV}$. Components sensitive to higher energies show a slower fall of the amplitude with increasing R_c . Thus, for the neutron component at sea level for $\Delta H = -500 \,\text{nT}$ the amplitude varies from 6% for $R_c = 8 \,\text{GV}$ (this is the maximum amplitude) to 4.3% for $R_c = 15 \,\text{GV}$. For the neutron component with $\Delta H = -400 \,\text{nT}$ at mountain and sea level the zone of maximum lies at $R_c = 3.7 \,\text{GV}$ and 7.9 GV, respectively, and for the hard component at sea level, the zone of maximum lies close to the equator.
- 5. The increase predicted for the hard component is quite peculiar. Up to $R_c < 3 \text{ GV}$ the effect is practically absent. Even for $R_c = 5 \text{ GV}$ the amplitude for $\Delta H = -50$ gammas is only 0.01% and for $\Delta H = -500 \text{ nT}$ only 0.2%. However, starting from this value, the amplitude increases rather strongly for large ΔH and reaches at $R_c = 8 \text{ GV}$ already a value of about 0.7% for $\Delta H = -500 \text{ nT}$, 0.42% for $\Delta H = -300 \text{ nT}$ and 0.12% for $\Delta H = -100 \text{ nT}$. Note that for $\Delta H = -100 \text{ nT}$ the maximum lies close to 8 GV, but that for large ΔH it is shifted towards $R_c = 12 \text{ GV}$.

Of course, a comparison of these results with the observed data about the storms of September 13, 1957 and February 11, 1958, discussed in Kondo et al. (1960), is most interesting. Though in Kondo et al. (1960) important data were found about the latitude distribution of the effect and its nature, it is desirable to extend these results, including data about the hard component and more stations in order to also investigate the longitude distribution.

6.14.3 The Latitude–Longitude Distribution of the CR Increase Effect of September 13, 1957

In analyzing of Dorman et al. (1961) of the CR intensity increase of September 13, 1957 observations with 49 instruments were used, including 33 neutron monitors and 16 ionization chambers and counter telescopes for the muon component. The stations were divided into nine latitude–longitude groups, as shown in Table 6.8.

The resulting curves in each group are shown in Fig. 6.54 (panels a and b, for neutron and muon components, respectively). The lower set gives mean graphs for each longitude zone.

Figure 6.55 shows for comparison the changes of the H-component of the geomagnetic field on September 12–13, 1957 at low-latitude observatories.

Evidently the increase differs strongly for different stations. Medium-latitude European stations show the largest amplitude; here the average magnetic threshold was 4.6 GV and the increase took place chiefly during the daytime. The amplitude in the high-latitude European stations, with mean threshold 1.8 GV, is considerably smaller, as expected. An analogous situation with smaller amplitudes is found in the

Latitude	Longitude	Component	Number of stations	$\begin{array}{c} \langle \mathbf{R_c} \rangle \\ (\mathrm{GV}) \end{array}$	Average longitude
High	America	Neutron	8	1.36	86° W
0		Muon	1	1.3	95° W
Medium	America	Neutron	3	3.2	$108^{\circ} \mathrm{W}$
		Muon	3	3.0	99° W
Low	America	Neutron	4	11.1	92° W
		Muon	2	11.8	$87^{\circ} \mathrm{W}$
High	Europe	Neutron	6	1.8	18° E
-	_	Muon	3	2.4	3° E
Medium	Europe	Neutron	6	4.6	22° E
	_	Muon	2	4.2	14° E
High	Asia	Neutron	3	2.2	151° E
-		Muon	2	1.2	149° E
Low	Asia	Neutron	3	14.0	121° E
		Muon	3	14.5	$70^{\circ}\mathrm{E}$

Table 6.8 Classification of groups of stations for the analysis of the effect of increase of CR intensity of September 13, 1957 (According to Dorman et al., 1961)



Fig. 6.54 CR intensity variation on September 12–13, 1957: **a** neutron component; **b** muon component (From Dorman et al., 1961)

American zone. Also, the Asiatic zone shows smaller amplitudes than the European zone. Thus the effect does not only depend on latitude, but also strongly on longitude. This, in our opinion, important property has far-reaching consequences. Before discussing the nature of this asymmetry, we also consider the CR increase during the magnetic storm of February 11, 1958. Here we note only that the observed dependence on latitude agrees rather well with the computations above, based on the theoretical model of Obayashi (1959) and on the method of coupling functions. In fact, Fig. 6.55 shows that the *H*-component during the magnetic storm changed by $-400 \,\text{nT}$, so that from Figs. 6.50–6.53 we should expect at the threshold $R_c = 2-3 \,\text{GV}$ an amplitude of about 1.5% in the neutron component at sea level and about 3% in the neutron component at mountain level. In the interval from 4 to 6 GV (medium latitude), an amplitude of about 4% should be expected in the neutron



component at sea level. In the R_c interval 10–15 GV (low latitude) this is about 3.5% for the neutron component at sea level and about 4.5% at mountain level. The data in Fig. 6.54a are seen to agree well with these estimates. Figure 6.54b gives analogous data for the muon component. The observed effect is found to be considerably larger than the expected one. For instance, for high-latitude European stations, with a geomagnetic threshold of 2.4 GV, where the expected effect is smaller than 0.03%, observations give an amplitude of about 2%. Only at low latitudes can a more or less satisfactory agreement with the observations be found, e.g., in America where the observed amplitude of increase is about 1%, the expected value is 0.7%. We stress that the intensity increase for the European stations, where the largest difference with theory is found, took place in the daytime. The data about the muon component show that some other mechanism, appearing chiefly in particles of higher energy, was acting as well.

6.14.4 The Latitude–Longitude Distribution of the CR Increase Effect on February 11, 1958

We shall now consider the CR intensity increase on February 11, 1958. The data available from 38 neutron monitors and 22 counter telescopes were again grouped as shown in Table 6.9.

Figure 6.56 shows the change of the geomagnetic field.

Figure 6.57 (panels a and b) gives the results for the neutron and muon components averaged over groups of stations.

Latitude	Longitude	Component	Number of stations	$\langle R_{\rm c} \rangle$	Average
			or stations	(01)	Tongitude
High	America	Neutron	9	1.4	$90^{\circ} \mathrm{W}$
		Muon	4	1.3	$95^{\circ} \mathrm{W}$
Medium	America	Neutron	3	4.5	$98^{\circ} \mathrm{W}$
		Muon	3	3.0	99° W
Low	America	Neutron	5	12.0	$80^{\circ} \mathrm{W}$
		Muon	2	11.8	$87^{\circ} \mathrm{W}$
High	Europe	Neutron	10	2.5	15° E
		Muon	4	2.0	32° E
Medium-high	Europe	Neutron	5	3.3	6° E
		Muon	2	2.4	0° E
Medium	Europe	Neutron	3	5.3	36° E
	-	Muon	2	4.2	14° E
Low	Europe	Neutron	2	16.0	55° E
	-	Muon	2	14.9	60° E
High	Asia	Neutron	4	2.4	149° E
0		Muon	3	1.2	$144^{\circ} \mathrm{E}$
Low	Asia	Neutron	2	12.2	142° E
		Muon	2	9.0	145° E

Table 6.9 Classification of groups of stations for the analysis of the effect of CR intensity increaseat February 11, 1958 (According to Dorman et al., 1961)



Comparison with the expected results shows that an analogous situation occurs as in Section 6.14.3. The largest amplitude of the intensity increase was observed for the neutron component in the high and medium-high European zones, where the increase took place in the afternoon. The amplitude was also considerable for lowlatitude stations in Europe, with average geomagnetic threshold 8.5 GV but much smaller in the high-latitude zone with geomagnetic threshold 1.8 GV. Comparison of different longitude zones in groups with equal geomagnetic thresholds shows



that the amplitude again depends strongly on longitude. In the Asian high latitude zone, where the increase took place during the night, the amplitude was considerably smaller than in the corresponding European zone, both with cutoff threshold near $\langle R_c \rangle \approx 2.4 \,\text{GV}$. It should be noted that again the dependence on longitude appears more clearly for stations with small geomagnetic threshold than for low-latitude stations. The data on the muon component show that besides the already noted discrepancy of a larger amplitude than the expected value, there is also a shift of the

phase in one or other direction, so that it approaches local noon. This indicates that a considerable solar-daily variation of another kind is superposed on the increase effect for the muon component (see Sections 6.15 and 6.16).

6.14.5 Main Properties of the CR Intensity Increase During the Main Phase of a Magnetic Storm

The preceding sections show that (Dorman et al., 1961):

- 1. Analysis of the vast material of the worldwide net of stations on the neutron and muon components confirms the conclusion of Kondo et al. (1960) that, for the events considered, the observed increase of CR intensity is mainly connected with an actual variation of the geomagnetic threshold during the main phase of a magnetic storm.
- 2. The CR increase in the muon component cannot be completely caused by the change of geomagnetic threshold. Here an important role is played by the solar-daily variation, disturbed during magnetic storms.
- 3. The fact that the amount of the CR increase depends on longitude, indicates that the variation of the geomagnetic threshold depends both on the latitude of the point of observation and on local time. Hence the theoretical model of Obayashi (1959), which assumes axial symmetry, has to be modified in order to include a longitude dependence. Possible mechanisms of such asymmetric variations of cutoff rigidity have been considered in Section 6.12.

The largest perturbations must be found at the dayside; on the nightside the dimensions of the cavity must be larger and the variations of the field smaller, so that the change of the cutoff rigidity at this side is smaller than at the dayside. The main conclusion that the observed increase during the main phase of magnetic storms cannot be explained completely by the direct influence of the geomagnetic field, but is too large in the muon component and at high latitudes, has been confirmed by investigations during other magnetic storms (Kolomeets et al., 1963; Dorman et al., 1965b; Chirkov et al., 1965; Dorman and Chkhetiya, 1965; Kolomeets and Pivneva, 1966). The intensity increases during the magnetic storms of August 18 and September 13, 1957 and February 11 and August 17, 1958 were analyzed in Dorman et al. (1965b). After excluding the Forbush effect, some short-period ($\sim 4-6h$) increases with amplitude more than twice the statistical error, were detected; they are observed all over the globe and occur some days after the onset of the magnetic storm. The longitude-rigidity distribution of these fluxes was found and the dependence of their amplitude on geomagnetic cutoff rigidity did not contradict the values expected from the variation of cutoff rigidity with variation of the geomagnetic field. A CR intensity increase of short duration, observed against the background of the Forbush decrease of July 15, 1959 by the flux of solar cosmic rays, was analyzed in Dorman and Chkhetiya (1965). Study of the distribution over the earth showed that, though the effect is observed simultaneously at all stations, its value reaches a maximum at stations where the local time is close to noon. At the same time, a transient increase of the *H*-component of the geomagnetic field was detected with its maximum near midday. The latitude variation both of the effect in the CR and of the change in the *H*-component around noontime shows a maximum at latitude $\sim 55^{\circ}$.

6.14.6 Statistical Properties of the CR Increase Effect During the Main Phase of the Geomagnetic Storm

The effect just described, of CR intensity increase at minimum Forbush effect during magnetic storms, follows important statistical laws discovered by Kondo (1961, 1962). The 58 magnetic storms observed during the IGY were divided into two classes according to whether the chromospheric bursts causing these storms were or were not accompanied by radio-bursts of type IV. Each of these classes was in turn subdivided into three groups according to the strength of the magnetic storms (strong, moderate, and weak). The results of averaging by superposition of epochs the intensity variations of the neutron component at high-mountain stations for the three groups of storms of the first class (accompanied by radio-bursts of type IV) are shown in Fig. 6.58.

For the same class of storms, the results for the neutron component at sea level are given in Fig. 6.59, which also shows the mean variations of the *H*-component of the geomagnetic field from observations at Kakioka.

Fig. 6.58 Average intensity curves of the neutron component at mountain level during magnetic storms connected with radiobursts of type IV. Stations: 1 – Huancayo; 2 – Mt. Norikura; 3 – Zugspitze; 4 – Mt. Washington; 5 – Sulphur Mountain (According to Kondo, 1961, 1962)



Fig. 6.59 The same as in Fig. 6.58, but for the neutron component at sea level. Stations: 1 – Rome, 2 – Weissenau; 3 – Ottawa; 4 – Mawson. The bottom curve 5 shows the H-component at Kakioka (According to Kondo, 1961, 1962)





For magnetic storms of the second class (not accompanied by radio-bursts of type IV) the average results for high-mountain neutron monitors and also data about the *H*-component at Kakioka are given in Fig. 6.60.

Figures 6.58 and 6.59 show that magnetic storms of any strength connected with radio-bursts of type IV considerably lower the CR intensity, whereas storms of the second class (Fig. 6.60), especially of moderate and weak strength, produce practically no Forbush effect. From this it follows that in the first case, the particles are scattered considerably by the frozen magnetic fields of the corpuscular streams. In the second case, the scattering was insignificant. The increase effect, on the other hand, shows the interesting result that this is observed mainly during strong magnetic storms with large variations of the H-component of the geomagnetic field, irrespective of whether these are accompanied by radio-bursts of type IV or not. This means essentially that the increase effect does not depend on the presence of frozen magnetic fields in the corpuscular streams, but is chiefly determined by the kinetic energy of the plasma of the solar wind stream and the way in which this energy interacts with the geomagnetic field. It should be noted that the increase effect (especially during strong magnetic storms) is on average so strong that in many cases it even surpasses the decrease by the Forbush effect. Therefore, when studying the latter and particularly in determining the energy spectrum of the Forbush effect, it is absolutely necessary to apply corrections for the increase effect. For instance, Dorman and Tyasto (1964) have analyzed the diurnal variation of CR during the magnetic storm of October 25, 1960, which was not accompanied by any visible Forbush effect. They showed that this magnetic storm actually affected CRs, but that the reduction of intensity by the Forbush effect was fully masked by the CR intensity increase. From the variations of the horizontal component of the geomagnetic field they computed the expected intensity increase at an equatorial station. After corrections had been applied for this effect, a Forbush effect with amplitude $\sim 3\%$ became apparent. Kuzmin and Krymsky (1965) suggested that the separation of CR variations due to a change in the cutoff threshold during magnetic perturbations should be studied by comparing records from two apparatuses with closely equal coupling functions, which would have the same sensitivity for sudden variations but a different sensitivity for changes of the geomagnetic cutoff.

6.14.7 Possible Influence of Small Magnetic Perturbations on Cosmic Rays

Warwick (1963) studied the effect of the geomagnetic crochet on CR intensity. He showed that the expected increase of neutron intensity must be 0.05%. But the observed effect is 0.2–0.3%, which means that it must chiefly be due to another cause. Wilson and Nehra (1963) show that the increase observed in Warwick (1963) is mainly due to incidence of solar CRs.

6.14.8 Earlier Detection of the Effect of Compression of the Magnetosphere in Cosmic Rays

Effects of magnetosphere compression in CRs have been studied by Patel and Chasson (1967) from neutron observations at the worldwide network of stations during August–December 1961. By superposition of epochs, they showed that expansion of the magnetosphere, as observed by means of magnetic measurements on Explorer-12, leads to an increase, and compression to a decrease, of CR intensity. The results agree with those expected from the theory (see Sections 6.6–6.13). Balloon observations of the increase in cutoff rigidity above Minneapolis and Churchill in a period of compression of the magnetosphere during the positive phase of the magnetic storm with a sudden onset at 11.12 UT on August 30, 1966 were performed by Earl and Rygg (1967).

6.14.9 Earlier Direct Observations of the Cutoff Variations by Means of Measurements on Balloons and Satellites and from Polar Cap Absorptions

Direct measurements by Akasofu (1963) on the satellite Explorer-7 in April 1960, first showed that protons with energy >30 MeV are present during moderate magnetic disturbances down to geomagnetic latitude $\lambda_{min} = 59^{\circ}$, whereas in Störmer's theory for such particles, $\lambda_{min} = 69^{\circ}$. This was explained by assuming that besides the ring current, the limitation of the geomagnetic field at a distance of 8-12 earth's radii (caused by the influence of the solar wind) is important. Direct measurements of changes of cutoff rigidity from balloon observations of solar CRs were first made by Freier (1962). He showed that whereas in a quiet period, the cutoff rigidity above Minneapolis is 1.2 GV, during the magnetic storm of July 1959, it decreased at least to 0.7 GV (the cutoff being of exponential character $\propto \exp[-(R-R_c)/0.065]$, where R and R_c are measured in GV). An analogous decrease of cutoff rigidity was detected by means of solar CRs during the magnetic storms of March 26 (Freier et al., 1959), May 12, 1959 (Ney et al., 1959), and September 4, 1960 (Earl, 1962). Further extensive information about rigidity variations obtained by Leinbach et al. (1965) from riometer observations of polar cap absorptions on March 23, April 10, July 7, August 16, 21, 22, 26, 1958; May 11, July 10, 14, and 16, 1959, at the stations Thule (geomagnetic latitude 88° N), Barrow (68.5° N; McIlwain parameter L = 7.8), Fort Yukon (66.7° N; L = 6.4), College (64.65° N; L = 5.5), Farewell $(61.4^{\circ} \text{N}; L = 4.25)$, and King Solomon Isles $(57.45^{\circ} \text{N}; L = 3.3)$ confirmed that the polar cap may be divided into two regions: north and south of geomagnetic latitude 65° N (L = 5.5). In the first region, the time development of polar cap absorptions does not depend on geomagnetic activity and is determined completely by the time variation of the solar CR flux. It is characteristic that the ratio of the absorptions at College and at Thule is >0.8. In the second region (geomagnetic latitudes $55-64^{\circ}$ N), the polar cap absorptions are determined chiefly by the variations of geomagnetic activity. For instance, it was shown that, while before the onset of magnetic storms, the absorption at Farewell (L = 4.25) is only ~ 0.14 of that at Thule, during magnetic storms the amplitudes of the absorption at the two points are equal. At King Solomon (L = 3.3) before the onset of magnetic storms, the polar absorptions are so small that their presence can hardly be established. But during magnetic storms they become at this station comparable with those at Thule. Fan et al. (1964) discussing the global distribution of the intensity of protons with energy >1.5 MeV, measured on an oriented satellite with polar orbit, also found a direct effect: the cutoff rigidity was reduced and the cutoff threshold was displaced from 75° to 65° geomagnetic latitude. Hakura (1966) constructed from data about polar cap absorptions and direct observations on balloons and satellites, a curve showing the latitude variation of the ratio $R_{\rm cobs}/R_{\rm cSt}$, where $R_{\rm cobs}$ is the observed cutoff rigidity and $R_{\rm cSt}$ is the cutoff rigidity computed by Störmer's theory. It was shown that at latitudes 40–50° this ratio is about 1, then decreases smoothly to $R_{\rm cobs}/R_{\rm cSt} \sim 0.7$ at latitudes $55-65^{\circ}$ and steeply falls to zero at latitudes above 65° . We shall see in Section 6.17 that the tail of the earth's magnetosphere is essential in interpreting these results.

6.15 Variations of the Geomagnetic Field and Local CR Anisotropy

6.15.1 The Asymmetry in the Variation of the CR Cutoff Rigidity for East–West Directions in Ahmedabad and North–South Directions in Moscow

According to Sarabhai et al. (1959), the asymmetry in the variation of the CR cutoff rigidity during the main phase of a magnetic storm must lead to peculiar solar-daily variations of CR with properties quite different from those of ordinary solar-daily variations, the source of which lies far from the sphere of action of the geomagnetic field (see Fig. 6.61).

Sarabhai et al. (1959) have argued that during magnetic storms the maximum of the CR diurnal variation is not only shifted in time and in magnitude, which might still be explained by variations of the "distant" source formed by a magnetized corpuscular stream enclosing the earth, but that other properties of the diurnal variation, observed with crossed telescopes, require the assumption of a "local" source of CR anisotropy. We see in Fig. 6.61 that in disturbed days the phase difference between the diurnal vectors for west and east directions decreases considerably.



Fig. 6.61 Average CR solar-diurnal variations in the east and west directions in 1957/58 at Ahmedabad: **a** days with high geomagnetic disturbances; **b** medium disturbances; **c** low disturbances (According to Sarabhai et al., 1959)

This problem was discussed in detail by Dorman and Inozemtseva (1961), who used, for determining the dependence of the solar-diurnal CR variation from the direction of incidence of the primary particles during geomagnetic disturbances, data of the azimuth telescope measuring the variation of CRs from the vertical direction and also at zenith angle 45° north and south at Moscow during eight magnetic storms from February to July 1960 (see Fig. 6.62).

In Fig. 6.62 the data were averaged over the following periods: (1) 2 and 1 days before the onset of the magnetic storm; (2) on the day of, and one day after, the beginning of the storm; (3) 2–4 days after the onset; (4) 5–7 days after the onset; (5) 8–10 days after the onset of the storm. Panel a in Fig. 6.62 gives the resulting first harmonics at Moscow in each of the five periods. The temperature effect was eliminated (panel b in Fig. 6.62) by using the harmonic coefficients of the temperature corrections for the muon component at the intermediate latitudes determined by Glokova et al., 1958 (see a review in Dorman, M2004, Chapter 7). The difference north–south is represented in panel c in Fig. 6.62.



Fig. 6.62 First harmonic of CR solar-diurnal variation for north and south directions from Moscow data: **a** with corrections for aperiodicity and barometric effect; **b** with corrections for aperiodicity, barometric and temperature effect; **c** – difference between the first harmonics north–south. In **a** and **b** full arrows refer to recordings with the southern telescope; dashed arrows to the northern telescope. The numbers appended to the vectors refer to different time intervals, as described in the text (According to Dorman and Inozemtseva, 1961)

6.15.2 The Analysis of CR Cutoff Rigidity Asymmetry on the Basis of Directional Data in Capetown and Yakutsk, and NM Worldwide Network

The analysis described in Section 6.15.1 was extended in Dorman and Inozemtseva (1961) by also using the following data (all data were separated into five time intervals 1–5 as described in Section 6.15.1):

 Records of CR variations in directions with zenith angle 45° north and south by counter telescope at Capetown (33°58′E, 18°28′E) from October 1957 to September 1958 (six magnetic storms) – for results see Fig. 6.63.



Fig. 6.63 First harmonic of the CR solar-diurnal variation for directions north and south, from Capetown data. Symbols are the same as in Fig. 6.62 (According to Dorman and Inozemtseva, 1961)

The diagrams in Fig. 6.63 show that on days after the beginning of the magnetic storm, with or without corrections for temperature effect in the muon component, the maximum of the diurnal variation is shifted toward morning hours for the northern and southern directions (periods 2 and 3). Afterward, as the normal intensity becomes reestablished (periods 4 and 5) the phase of the first harmonic vectors shifts in the opposite direction, toward later time. The phase of the first harmonic of the difference curve also shifts, in different ways for different cases. Only period 5 at Capetown forms an exception, both in panels b and c in Fig. 6.63.

2. Observations of the neutron component in the same period from October 1957 to September 1958 (six magnetic storms) which were separated into three groups of stations: group I – ten high-latitude stations with average cutoff rigidity $\langle R_c \rangle = 1.8 \,\text{GV}$; group II – five medium-latitude stations $\langle R_c \rangle = 5.2 \,\text{GV}$; group III – five low-latitude stations $\langle R_c \rangle = 13.7 \,\text{GV}$. For results, see Fig. 6.64.



Fig. 6.64 First harmonic of the diurnal variation for the neutron component from data of three groups of stations; I – high latitude, II – medium latitude. III – low latitude. Symbols as in Fig. 6.62 (According to Dorman and Inozemtseva, 1961)

From Fig. 6.64 it can be seen that the shift of the maximum of the diurnal variation toward morning is also observed in the neutron component. Figure 6.64 shows, for stations of group I, an evident shift of vector 2 over nearly 6 h toward morning and an amplitude increase by as much as a factor of 3. Later the amplitude decreases gradually and the time of maximum returns to normal. For stations with a larger cutoff rigidity (5.1 GV), the character of the variation of the CR solar-diurnal effect practically does not change. However, when the cutoff rigidity increases to 13.7 GV the vector of the diurnal wave is considerably more stable: the time of maximum varies by not more than 2 h and the amplitude by not more than a factor of 2. The phase differences between north and south before the temperature correction has been applied do not show an apparent regularity. However, after correction for the temperature effect, this phase difference remains approximately constant.

3. Data of Kuzmin et al. (1960) about variations of the hard component at Yakutsk, obtained with telescopes directed north and south under zenith angle 30° in July 1959 at sea level (0 m w.e.) and at depths 7 and 20 m w.e. The harmonic analysis

for Yakutsk station in July 1959 gave very interesting results. The temperature corrections were taken from Kuzmin (1960), based on fourfold sounding of the atmosphere above Yakutsk from July 1957 to July 1958. Final results are given in Fig. 6.65.

Figure 6.65 represents the change of the mean diurnal vector for directions north and south, obtained by averaging over three levels 0, 7, and 20 m w.e. without and with correction for temperature effect.

The corresponding difference vectors are given in Fig. 6.66.

The diagrams in Figs. 6.65 and 6.66 again show, during the magnetic storm of July 1959 for direction north, a rather pronounced phase shift of the CR diurnal



Fig. 6.65 First harmonic of the diurnal variation from data at Yakutsk in July 1959, averaged over sea level and depths 7 and 20 m.w.e.: **a** with correction for a periodicity and barometric effect; **b** with correction for aperiodicity, barometric and temperature effects. Drawn vectors – southern telescope; dashed vectors – northern telescope. Periods: (1) 8–10 July; (2) 12–14 July; (3) 16 and 17 July; (4) 22–24 July (From Dorman and Inozemtseva, 1961)



Fig. 6.66 First harmonic of the diurnal variation of the curve in the difference north–south from Yakutsk observations. Symbols as in Fig. 6.65 (From Dorman and Inozemtseva, 1961)

wave toward morning, in agreement with the results for Moscow and Capetown. For direction south the phase is displaced toward evening in periods 3 and 4 as compared with periods 1 and 2. As in the earlier examples, the amplitude of the CR diurnal variations increased strongly on days with a strong decrease of CR intensity. After correction for spurious diurnal variation, the amplitude of the diurnal wave on the day of the onset of the magnetic storm decreased considerably, but remained about 1.5–2 times larger than before the magnetic storm.

6.15.3 The Main Results and Discussion on CR Cutoff Rigidity Asymmetry During Magnetic Storms

The analysis of the nature of the disturbance of CR anisotropy during magnetic storms in Dorman and Inozemtseva (1961) were based on the data from several directed muon telescopes and many neutron monitors, which agreed well among each other. The following conclusions may be drawn from the data given in Sections 6.15.1 and 6.15.2.

- 1. For directions north and south and for vertically incident particles (from neutron monitor observations), a regular phase shift is observed for the diurnal variation toward earlier hours during magnetic perturbations after the onset of a magnetic storm. The phase shift also continues after the end of the magnetic storm during a long period of recovery. This phenomenon is connected with the action of solar corpuscular streams on CR and we shall not discuss it here.
- 2. During magnetic storms the difference vector north–south changes considerably. This is highly important for, if the disturbance in the anisotropy were due to distant sources only and the spectrum of the original diurnal variation would change only insignificantly, the phase difference between the variations from north and south would have to remain constant, since it is determined only by the curvature of the trajectories in the geomagnetic field. Hence, it is clear that during geomagnetic perturbations, there must be a source in the direct neighborhoods of the earth where the geomagnetic field influences the trajectories of the particles. At the same time, the difference vector behaves differently for the chosen groups of magnetic storms. Thus, the properties of the local source seem to vary from one storm to the next. The nature of the local source of anisotropy is considered in Section 6.15.5.

6.15.4 The Anomalous CR Diurnal Variation During the Main Phase of the Magnetic Storm of February 11, 1958

Dorman and Inozemtseva (1962) analyzed in detail the anomalous CR diurnal variation during the main phase of the magnetic storm of February 11, 1958 from



Fig. 6.67 The maximum size of the increase effect versus geographic longitude from observations of the neutron component at 40 CR stations (From Dorman and Inozemtseva, 1962)

observations with crossed telescopes at Capetown and 40 neutron monitors. It was found that the increase effect during the main phase of the magnetic storm is clearly anisotropic (see Fig. 6.67).

6.15.5 On the Nature of CR Anisotropy Asymmetry: Local and Non-local Sources

In Dorman and Inozemtseva (1962), from observations of the variations of *H*-component of the geomagnetic field at the equatorial stations Guam and Jarvis, the expected geomagnetic variation of neutron intensity was computed for moments at intervals of 2h for all 40 stations by means of the graphs of Fig. 6.50 and the curve of Fig. 6.67. Two alternative assumptions have been made in these computations. The first assumption is that the isotropic part is due to the formation of a cavity and its amplitude depends on ΔH , but that the anisotropic part does not depend on ΔH and is connected with a source of non-local origin. This agrees with all observations except those for the stations of the western hemisphere (where a considerable deviation is observed in the evening) and for the high-latitude stations where the amplitude seems correct, but where an important difference in the form of the curves is observed. This difference may be connected with the following. Tsunekichi (1961) showed, from data of neutron monitor world network during the IGY, that the non-dipole terms of the geomagnetic field for a distant source cause the phase of the diurnal variation to change by a time of a few hours, not only depending on geomagnetic latitude but also on the longitude of the station. It is to be expected that the discrepancy noticed for the American stations under the first assumption be partly connected with this effect, though further analysis should also take the energy spectrum of the variation and the perturbation of the trajectories in the geomagnetic field into account. The second assumption is that the isotropic as well as the anisotropic part of the increase are entirely of a local nature and arise within the cavity. This assumption gives somewhat better agreement for the intermediate latitudes, but does not at all explain the effects in the high-latitude region. The disagreement of the second assumption with observation may be connected with the following circumstances.

- 1. The results of Obayashi, 1959 (see Section 6.14) on which the computations in Section 6.14 are based, were obtained for vertical incidence, though obliquely incident particles which have a different cutoff rigidity, depending on azimuth, give an important contribution to the counting rate of neutron monitors. Thus at high latitudes the effect must differ from zero, in agreement with the observations.
- 2. Obayashi's computations (Obayashi, 1959) did not take into account that the magnetic field at high latitudes is far from homogeneous. It was assumed that the additional field superposed on that of the earth during the main phase of the magnetic storm can be represented by a homogeneous field in a direction opposite to the geomagnetic dipole. However, observations show that the additional field at high latitudes differs considerably from the homogeneous field.
- 3. The plasma stream blows the magnetic lines of force away and the distortion of the geomagnetic field thus will differ from the isotropic distortion assumed in Obayashi (1959).

We conclude that the isotropic part of the increase may be due entirely to the decrease of the cutoff rigidity by the distortion of the geomagnetic field during the main phase of the magnetic storm. The anisotropic part of the increase effect may have at least two causes. One of these is a distant source, acting outside the sphere of the geomagnetic field and probably connected with the action of solar corpuscular streams, causing a distorted variation. This cause gives the ordinary perturbed diurnal variation that may, in first approximation, be neglected in explaining the increase effect at intermediate latitudes. The other cause is a local source influencing CRs within the sphere of action of the geomagnetic field; the existence of such a source follows also from the data on harmonic analysis with crossed telescopes given above. Both causes act in the same direction, giving a maximum in daytime. In records with neutron monitors at high latitudes still another cause of intensity increase during the main phase of a magnetic storm may appear: a stream of low-energy particles from the sun into the magnetic trap of the corpuscular stream. This cause appears quite strongly in observations at high latitudes by means of sounding balloons and artificial satellites. Inozemtseva (1964) has investigated the relation of the local source of anisotropy during the storm of February 11, 1958 with the observed variations of the *H*-component of the geomagnetic field. Sarabhai and Rao (1961) studied the local source of diurnal variation from observations in 1957/58 at Ahmedabad (India) with directional CR telescopes. Anisotropic changes of cutoff rigidity were also detected by Hatton and Marsden (1962), from the planetary distribution of the increase of solar CR intensity from a chromospheric burst during the magnetic storm of November 12, 1960. Thus, careful investigation of the increase of CR intensity during the main phase of magnetic storms established the fact that the changes of the magnetosphere are anisotropic and in particular that the geomagnetic cavity is stretched out in the direction away from the sun. The latter fact has since been confirmed by numerous direct measurements of the magnetic field on rockets and satellites (see Section 6.17).

6.16 CR Lunar-Daily Variation and Tidal Effects in the Earth's Magnetosphere

6.16.1 The Discovery of Lunar-Daily CR Variation and Discussion on Its Possible Origin

Bagge and Binder (1959) showed that, when observations of CR intensity are averaged, a variation with a period of one lunar day and amplitude of some tenths of a percent appears. These variations were obtained by averaging observations taken at Kiel during the period July–December 1957. Later Bagge and Binder (1962) found from observations of the muon and neutron components until June 1961 that the amplitude of the variation gradually decreases in the course of time (Fig. 6.68).

In Bagge and Binder (1962), a stable wave was found with amplitudes 0.25% for the neutron component and 0.12% for the muon component, and nearly equal time of maximum 12–16 h after culmination of the moon at Greenwich. The question arose whether the CR lunar-daily wave is real. This was all the more pressing since it was hard to find a possible cause for this variation. The effect of the lunar shadow cannot exceed 0.01\%. Computation of the influence of a hypothetic magnetic field of the moon on CR trajectories also showed that this could not explain a considerable part of the CR lunar-daily variation. Moreover, measurements aboard a Soviet cosmic rocket by Dolginov et al. (1961) soon showed that the strength of the magnetic field of the moon cannot exceed 20 gammas at the moon's surface and its magnetic moment is at least 10^4 times smaller than that of the earth. Ness et al. (1967a) showed that the perturbation by the moon of the magnetic fields in



Fig. 6.68 Amplitude of the lunar-daily variation from July 1957 to June 1961, from observations at Kiel (From Bagge and Binder, 1962)

the solar wind is very small. The direct influence of the geomagnetic field on the trajectories, as a result of lunar-daily variations of the geomagnetic field, cannot be important either, since the magnetic *L*-variations have a very small amplitude (see the review in Mitra, 1955). Also, the influence of the moon on magnetic activity (on the index Ap) is quite small (Rassbach and Dessler, 1966). The hypothesis has been advanced (Ness et al., 1967a) that the lunar-daily variation of CR may be due to lunar-tide motions of the plasma and the geomagnetic lines of force near the earth in the region of the radiation belts.

6.16.2 Amplitude Modulation of CR Solar-Daily Wave by the 27-Day Effect and Formation of Spurious CR Lunar-Daily Variation

In principle, the variations discovered in Bagge and Binder, (1959, 1962) can be quite spurious since, according to Dorman (1961) and Krymsky (1962), the 27-day modulation in amplitude and phase of the CR solar-daily variation must lead to three terms with periods 23.2, 24, and 24.9 h, i.e., one of the side harmonics will have a period close to a lunar day. If the lunar variation is completely spurious, the two side harmonics must have equal amplitudes. In fact, let us consider in the first the 27-day modulation in the amplitude of CR solar-daily variation:

$$I(t) = A(t)\cos(\omega_1 t + \varphi_o), \qquad (6.59)$$

where $\omega_1 = 2s\pi/24$, *t* is measured in hours, and

$$A(t) = A_o \cos\left(1 + \alpha \cos\left(\omega_2 t\right)\right). \tag{6.60}$$

In Eq. 6.60 $\omega_2 = 2\pi/(24 \times 27)$. From this it follows that

$$I(t) = A_o \left\{ \cos(\omega_1 t + \varphi_o) + \frac{\alpha}{2} \cos[(\omega_1 + \omega_2)t + \varphi_o] + \frac{\alpha}{2} \cos[(\omega_1 - \omega_2)t - \varphi_o] \right\}.$$
(6.61)

Thus, besides the CR solar-daily wave with amplitude A_o and frequency ω_1 corresponds to the period $T_1 = 24$ h, waves arise with frequencies

$$\omega_{\pm} = \omega_1 \pm \omega_2, \tag{6.62}$$

i.e., with periods

$$T_{\mp} = \frac{24 \times 27}{27 \pm 1} = \begin{cases} 23.143 \text{ hours,} \\ 24.923 \text{ hours.} \end{cases}$$
(6.63)

From Eq. 6.63 it is seen that one of the harmonics actually has a period of one lunar day. The amplitude of this wave according to Eq. 6.61 will be $A_o \alpha/2$. If $A_o \approx 1.5\%$ and $\alpha \approx 0.3$, the expected amplitude is more than 0.2% for the neutron component; for the muon component it is somewhat smaller.

6.16.3 Formation of Spurious CR Lunar-Daily Variation by the Phase Modulation of CR Solar-Daily Wave with a Period of 27 Days

Consider now the 27-day phase modulation of CR solar-daily variation:

$$I(t,\beta) = A_o \cos\left(\omega_1 t + \beta \cos\left(\omega_2 t\right)\right). \tag{6.64}$$

If $\beta \ll 1$ we find, developing Eq. 6.64 in a Taylor series in β and including terms of the order of β only:

$$I(t,\beta)I(t,0) + \beta \left(\frac{\partial I(t,\beta)}{\partial \beta}\right)_{\beta \to 0} + \frac{\beta^2}{2!} \left(\frac{\partial^2 I(t,\beta)}{\partial \beta^2}\right)_{\beta \to 0} + \dots$$

$$\approx A_o \cos(\omega_1 t) + A_o \beta \sin(\omega_1 t) \cos(\omega_2 t) \qquad (6.65)$$

$$= A_o \cos(\omega_1 t) + \frac{1}{2} A_o \beta \sin((\omega_1 - \omega_2) t) + \frac{1}{2} A_o \beta \sin((\omega_1 + \omega_2) t).$$

Evidently in this case, besides the first harmonic with period $T_1 = 24$ h, harmonics appear with periods determined by Eq. 6.63 and amplitude $A_o\beta/2$. For $A_o \approx 1.5\%$ and $\beta \approx 0.5$ (corresponding to a phase shift of 2 h) the amplitude of the spurious lunar-daily variation will be more than 0.3%.

6.16.4 Checking on the Properties of 27-Day Modulation of CR Solar-Daily Variation

Dorman and Shatashvili (1963) checked the problems described in Sections 6.16.2 and 6.16.3 by a special study of the 27-day modulation of the CR solar-diurnal variation of the neutron component all over the globe in July–December 1957 (when the 27-day variations of CR intensity were most evident). The 27-day modulation in the amplitude of CR solar-diurnal variation was found to be about 30%, and the modulation in phase of about 2 h.

Krymsky (1962) analyzed observations of the CR lunar-daily variation in 1957/58 in neutron and muon components. The amplitude of the first harmonic was found equal to $0.17 \pm 0.04\%$ and $0.06 \pm 0.01\%$, and of the second harmonic 0.06% and 0.015% for the neutron and muon components, respectively. Krymsky (1962) assumed that the wave with a period of a half-lunar day could be explained mainly by the tidal phenomenon in the atmosphere producing a dynamic effect in atmospheric pressure. As regards to the first harmonic, it may be connected with the above-mentioned 27-day modulation of the CR solar-daily variation. Thus, the problem of the lunar-daily variation turned out to be quite complicated and its properties must first be better known.

6.16.5 On the Possible Reality of the CR Lunar-Daily Variation

In order to decide whether the CR lunar-daily variation is real, Dorman and Shatashvili (1961) analyzed observations of the CR neutron component at Mt. Sulphur during two periods of observation: (a) July–December 1957; (b) July–December 1958. In period (a), a 27-day recurrence in CR intensity was evident, whereas in period (b) this was not observed. Averaging according to Eq. 6.63 over periods *T* equal to 23.14, 24.00, and 24.92 h for the two groups of data (a) and (b) shows that the variation with a period of 24.92 h is somewhat more pronounced and has a larger amplitude than that with a period of 23.2 h (see Fig. 6.69).



Fig. 6.69 Observational data from Mt. Sulphur over periods T = 23.14, 24.00, and 24.92 h: **a** July–December 1957; **b** July–December 1958 (From Dorman and Shatashvili, 1961)

These results show that the variation with period 24.92 h contains a real CR lunardaily wave besides the spurious wave due to modulation by the 27-day variation of the CR solar-daily effect.

6.16.6 The Dependence of the CR Lunar-Daily Variation on the Relative Positions of the Sun, Moon, and Earth

Bagge and Binder (1959) investigated the CR lunar-daily variation disregarding the relative positions of the sun, moon, and earth and found the average wave for a full lunar month. But if the actual CR lunar-daily variation is connected with the gravitational action of the moon on the outermost layers of the earth's atmosphere, then, since the influence of the gravitational field of the sun must also be important, the observed CR lunar-daily wave must be determined by the relative positions of the moon, earth, and sun. This effect was studied from continuous recordings of the neutron intensity, obtained at Climax, July 1957–December 1958 (Dorman and Shatashvili, 1961). Every lunar month was subdivided into 10 periods of 3 days each. Then, by superposition of epochs, the intensity curves were found for all 18 months of the IGY. These curves, each corresponding to the lunar-daily wave at a particular phase of the moon, still have to be corrected for the solar-daily parts. Let us introduce the following notations:

L – the pure CR lunar-daily wave at a phase of the moon, averaged over 3 successive days and over all identical positions in the entire IGY

S – the pure CR solar-daily wave for the entire period of the IGY (found by averaging over a period of 24 h; then waves with other periods disappear)

 S^* – transposed CR solar-daily wave (averaged over 3 successive days at the various phases of the moon);

 $L + S^*$ – curves representing the superposition of CR lunar-daily and CR solardaily variations and are obtained by superposition of epochs by averaging observations over 3 successive days at the various phases of the moon.

The computations then run as follows: first, the observations gave $L + S^*$; then S^* was found with the aid of S; subtraction of S^* from $L + S^*$ gave the required curves for L for each phase of the moon. Figure 6.70 gives the curves for $L + S^*$, S^* and L at full and new moon for the neutron component at Climax.

Figure 6.71 gives CR *L*-variation of the neutron component at Climax for each phase of the moon for the period July 1957–December 1958 (below each L-curve diagrams on the relative positions of moon, earth, and sun are shown).

Figure 6.71 also shows that the CR lunar-daily variation depends very much on the relative position of the sun, moon, and earth, reaching a maximum for full moon and a minimum at new moon. In addition, the phase of L-curves changes considerably. These changes clearly distinguish the *L*-variations of CRs from those of the geomagnetic field variation for which the period is half a lunar month (Mitra, 1955).



Fig. 6.70 Curves L + S*, S*, and L for full and new moon at Climax (From Dorman and Shatashvili, 1961)

6.16.7 Dependence of the CR Lunar-Daily Variation on Cutoff Rigidity

Because the largest effect is observed at full moon, the curves for $L + S^*$, S^* and L from observations of the neutron component at Mt. Sulphur, Zugspitze, Mt. Norikura, and Huancayo are represented in Fig. 6.72 for that phase only. All four stations are high in the mountains, with different cutoff rigidities (increasing from Mt. Sulphur to Huancayo). The data again refer to the IGY (July 1957–December 1958). The arrows indicate the moments at which the moon was at zenith for the corresponding station.

Figure 6.72 shows that the CR *L*-curves depend strongly on the geomagnetic cutoff rigidity. They are most pronounced at intermediate latitudes and their amplitude decreases closer to the geomagnetic equator.



Fig. 6.71 Curves L for the CR neutron component at Climax for each phase of the moon (From Dorman and Shatashvili, 1961)

6.16.8 Main Conclusions and Discussion on the CR Lunar-Daily Variation in Connection with Possible Tidal Effects in the Earth's Atmosphere and Magnetosphere

In the first approximation, the CR lunar-daily variation may be explained as follows (Dorman and Shatashvili, 1961). The gravitational forces of the moon and sun exert an influence on the plasma of the magnetosphere of the earth. This displaces the magnetic lines of force, frozen in the plasma at great heights. The influence of the disturbed geomagnetic field on CRs leads to the lunar-daily variation. This effect should be larger, the larger the distance of these layers from the earth. Let $r_{\rm SE} = 1 \,\text{AU} \approx 23000r_{\rm E}$ and $r_{\rm ME} \approx 60r_{\rm E}$ be the distances sun–earth and moon–earth, respectively, expressed in the earth's radii; $M_{\rm S}$ and $M_{\rm M}$ are the masses of sun and moon, expressed in the earth's mass; G is the acceleration of gravity at the surface of the earth (see Fig. 6.73).

At distance a from the center of the earth (expressed in the earth's radius as unit) the acceleration of the tidal force of the moon at point A (Fig. 6.73), i.e., the difference between the actual and the average acceleration at point A will be

$$G_{\rm M}(a) = \frac{GM_{\rm M}}{(r_{\rm ME} - a)^2} - \frac{GM_{\rm M}}{r_{\rm ME}^2} \approx \frac{2aGM_{\rm M}}{r_{\rm ME}^3},$$
 (6.66)



Fig. 6.72 Curves L + S*, S*, and L for full moon at four mountain stations Mt. Sulphur (cutoff rigidity for vertical direction 0.94 GV: According to Quenby and Webber, 1959), Zugspitze (3.33 GV), Mt. Norikura (9.13 GV), and Huancayo (14.18 GV) (From Dorman and Shatashvili, 1961)

where it is taken into account that $a \ll r_{ME}$. In the same way, we find for the tideraising force from the sun $2aGM_{C}$

$$G_{\rm S}\left(a\right) \approx \frac{2aGM_{\rm S}}{r_{\rm SE}^3}.\tag{6.67}$$

With the numbers $r_{\rm SE} = 2.3 \times 10^4$, $r_{\rm ME} = 60$, $M_{\rm S} = 3 \times 10^5$, $M_{\rm M} = 0.0125$, and $G \approx 10^3 \, \text{cm/s}^2$, we find

$$G_{\rm M}(a) \approx 1.2 \times 10^{-4} a \,{\rm cm/s^2}; G_{\rm S}(a) \approx 5 \times 10^{-5} a \,{\rm cm/s^2}.$$
 (6.68)



Fig. 6.73 Influence of the tidal force on the upper atmosphere and magnetosphere of the earth (not to scale)

The form of the surface, which in the static case must arise through the influence of the tidal forces, is shown in Fig. 6.73. However, the rotation of the earth makes the picture more complicated; spherical harmonics of higher order appear. The tidal oscillations, insignificant at small heights, increase considerably with increasing height and they have already a perceptible amplitude in the ionosphere. For instance, according to Mitra (1950), the tidal fluctuations of the height of the F₂ layer of the ionosphere reach an amplitude of about 20 km, the average elevation of the layer being about 280 km, which means that the fluctuation is about 7% of the entire height. An even larger amplitude is to be expected at heights of thousands and tens of thousands of kilometers. Because of the high conductivity of the plasma at such elevations and the large dimensions of the region occupied by the magnetic field ($L > 10^8$ cm) the time needed by the magnetic field for entering or leaving the plasma will be

$$T \approx 4\pi\sigma L^2 / 4\pi\sigma L^2 c^2 \ge 10^6 c^2 \ge 10^6 s \approx 10 \text{ days.}$$
 (6.69)

Thus, for motions of the plasma as a whole in a time of the order of one day, the magnetic lines of force may be considered to be frozen into the plasma and to be displaced together with it. Hence, in the uppermost, highly conductive layers of the earth's atmosphere we must expect tidal fluctuations of the magnetic field. Without entering into any resonance phenomena, we shall give some rough estimates. During about 10⁵ s, under the influence of the imposed force with acceleration $G_{\rm M}$ at distance a = 3, the displacement will be $\sim G_{\rm M}t^2/2\sim 25$ km, and by the influence of $G_{\rm S}$ it will be 8 km. Actually, resonance phenomena will play an important role and fluctuations with periods close to the resonance periods will be considerably strengthened. In computing these fluctuations not only should the gravitational attraction of the plasma by the earth be taken into account, which becomes much smaller at greater heights on account of the larger distance *a* and smaller density ρ (as $\rho G/a^2$) and on account of the increase of the centrifugal force, but also the force of the magnetic pressure $H^2/8\pi$ and the force of the stretching of the magnetic lines of force. For fluctuations of the lines of force with amplitude Δ , measured

in the earth's radius as unit, a relative change of the strength of the magnetic field $\sim 3\Delta/a$ should be expected. Thus, even if no account is taken of resonance phenomena, a change of the field $\sim 0.3\%$ should be expected, which may explain CR variations with amplitude of at least some tenths of a percent. The computations in Section 6.14.2 by means of the coupling coefficients show that changes of the geomagnetic field of $\sim 1\%$ must lead to neutron intensity variations at intermediate latitudes of about 2% or about 4% at sea level or mountain level, respectively; this has been confirmed experimentally. A complete description of the changes of the geomagnetic field, taking into account the influence of the tidal forces of the moon and sun on the plasma and the rotation of the earth, will necessarily be very complicated. Also, dynamo effects arising from the motions of the plasma in the upper atmosphere will be important. Anyhow, the results of Dorman and Shatashvili (1961) about the CR lunar-daily variations and their dependence on cutoff rigidity and on the configuration moon-earth-sun undoubtedly prove the reality of tidal motions of the plasma and the magnetic field in the outermost atmospheric layers. Further study of these phenomena requires not only detailed theoretical computations, but also direct measurements of the lunar-daily variations of the magnetic field and of the density fluctuations in the radiation belts with the aid of satellites and rockets.

6.17 The Influence of the Tail of the Earth's Magnetosphere on the CR Cutoff Rigidities

In Section 6.14.9 we discussed a number of experimental data about the geomagnetic cutoff rigidity R_c at high geomagnetic latitudes: its abnormally low value, its time variations connected with geomagnetic activity, and its pronounced dependence on local time. Whereas the values of R_c measured at low and intermediate latitudes may be explained by the theoretical modeling and calculations (for details, see Sections 6.11–6.14, and Chapter 3), the data for the high latitudes can only be explained by introducing a qualitatively new element. It has more and more become clear that the key for understanding the behavior of CR at high latitudes lies in the influence of the earth's magnetic tail.

6.17.1 Main Properties of the Tail of the Magnetosphere

Magnetometer measurements on satellites and rockets not only have shown that there are current systems in the earth's magnetosphere and that the magnetosphere is limited at the dayside, but these have also established the fundamental fact that the magnetosphere has a tail (Cahill and Amazeen, 1963; Ness et al., 1964; Ness, 1965). The earth's magnetic tail, formed by interaction of the solar wind with the geomagnetic field, plays an important role in the production of ring currents, geomagnetic perturbations and auroras (Axford et al., 1965; Dessler and Juday, 1965;

Axford, 1966; Akasofu, 1966; Behannon and Ness, 1966; Paddington, 1967). The strength of the magnetic field in the tail is about 40 gammas, and, according to magnetic data from IMP-3 (Ness, 1967) and measurements of plasma fluxes on Luna-10 (Gringaus et al., 1966), it certainly extends beyond the orbit of the moon. Data from Explorer 33 (Ness et al., 1967b) make it possible that it extends to distances of about 510,000 km. From data of Pioneer-7 it is not excluded that it reaches up to 900–1,050 earth's radii (Ness et al., 1967c). It should be noted that there are indirect data, based on observations on the flux of low-energy electrons from the sun at energies of some tens of keV which suggest that this tail even may extend to 0.25 AU (Lin and Anderson, 1966).

6.17.2 Probable Mechanism by Which the Earth's Magnetic Tail Influences the CR Cutoff Rigidities

The first estimates of the influence of the tail of the earth's magnetosphere on CR cutoff rigidities were made by Michel (1965). He showed that, if the extension of the tail of the magnetosphere is sufficiently large, low-energy particles will penetrate by diffusion into the tail and will reach the polar caps along the lines of force of the geomagnetic field. Hence, the cutoff rigidity in the regions of the polar caps may prove to be considerably smaller than expected in the presence of the field, arising from internal sources only, i.e., much smaller than determined in Chapters 2 and 3 for quiet conditions at high geomagnetic latitudes.

6.17.3 Approximate Position of the Curves of Constant Threshold at High Latitudes

In order to obtain an approximate estimate of the influence of the tail of the magnetosphere on the isolines of geomagnetic threshold, Reid and Sauer (1967) considered the following simple model: the field in the tail of the magnetosphere was assumed to be 40 nT and to extend from $7.3 r_E$ to $12 r_E$ in the equatorial plane (see Fig. 6.74).

Then, according to Reid and Sauer (1967), for geomagnetic latitude $\lambda = 65.9^{\circ}$ (corresponding to $r = 12 r_{\rm E}$) the geomagnetic threshold is zero. The relation between the threshold kinetic energy of vertically incident protons (in MeV) and geomagnetic latitude for this model and for the dipole field is shown in Fig. 6.75.

With the graph in Fig. 6.75, the isolines of geomagnetic threshold at high latitudes can easily be found. They are shown in Fig. 6.76 and agree much better with the experimental values discussed in Section 6.14.9 than with the isolines found if only the internal sources of the field are taken into account. For instance, for Minneapolis, inclusion of the first six harmonics gives a cutoff threshold of about 750 MeV (see Chapter 3) while the experimental values of McDonald (1957) give only about 250 MeV. The model just discussed gives about 400 MeV for Minneapolis.



According to Fig. 6.76, above College (Alaska) the cutoff threshold for protons must be about 1 MeV in agreement with the data of Leinbach et al. (1965) mentioned in Section 6.14.9, about the distribution of polar absorptions.

6.17.4 The Influence of the Earth's Magnetic Tail on the Trajectories of Protons with Energy 1.2 MeV

In order to calculate the influence of the earth's magnetic tail on protons with energy 1.2 MeV reaching the earth at altitude 2,000 km, Taylor (1967) computed, by the Runge–Kutta method in Gill's modification (1951), the motion of negatively charged particles ejected from the earth. The model of the magnetosphere (Taylor and Hones, 1965) is shown in Fig. 6.77, where the numbers next to the lines of force indicate co-latitude, i.e., $90^{\circ}-\lambda$. In all, 252 trajectories were obtained in the latitude range $60-80^{\circ}$ at intervals of 1° and the longitude range $0-360^{\circ}$ at intervals of 30°. Taylor (1967) showed that latitudes $\leq 65^{\circ}$ are unattainable for protons of this energy for any pitch angle ($0-90^{\circ}$) at 2,000 km and at any time of the day. On the dayside of the earth in the latitude range $65-75^{\circ}$ only those protons with energy 1.2 MeV fall which have large pitch angles at altitude 2,000 km. At the same time, protons with any pitch angles reach elevations 2,000 km at midnight at latitudes $>65^{\circ}$. These results completely explain the experimental data that 1.5 MeV protons reach the earth at abnormally low latitudes (see Section 6.14.9).



Fig. 6.75 Relation between proton energy and cutoff latitude λ given by Störmer theory (upper curve) and calculated from the model of Fig. 6.74 (lower curve); the broken curve is guessed (According to Reid and Sauer, 1967)

6.17.5 Channeling of Low-Energy Cosmic Rays in the Tail of the Earth's Magnetosphere

Gall and Jimenez (1967) and Gall et al. (1968) computed 150 trajectories of protons with energies from 1 to 500 MeV in order to find the cutoff rigidity at midnight at Kiruna (in the north of Sweden). They used the model of the magnetosphere of Williams and Mead (1965) shown in Fig. 6.78. The same figure also gives the trajectories of protons with energies 5, 7, 10, 20, 30, and 40 MeV according to Gall et al. (1968), vertically incident at Kiruna. The computed geomagnetic threshold at Kiruna is 47 MeV for the model of the central dipole, 104 MeV for an eccentric dipole, and 135 MeV for the field which includes the first six harmonics (see Chapter 3). The computations reported by Gall et al. (1968) give considerably lower values: 4 ± 1 MeV at night, 47 ± 2 MeV in daytime.

Gall et al. (1968) assume that the particles enter the tail of the magnetosphere at a distance $25 r_E$ and that then their trajectories are channeled in the tail as shown



Fig. 6.76 Contours of equal geomagnetic cutoff over North America near local midnight for the conditions appropriate to the model calculation. The individual contours are labeled with the proton energy in MeV (According to Reid and Sauer, 1967)



Fig. 6.77 Model magnetic field in the noon-midnight meridian. The axes are labeled in units of earth radii, and the field lines are labeled by their co-latitude at the surface of the earth (From Taylor and Hones, 1965)

in Fig. 6.78. The night-value $E_{\rm kc} = 4 \pm 1 \,\text{MeV}$ was found on the assumption that the field strength in the tail is $H_{\rm tail} = 40 \,\text{nT}$, but it critically depends on $H_{\rm tail}$: if $H_{\rm tail} = 30 \,\text{nT}$, then $E_{\rm kc} = 22 \pm 2 \,\text{MeV}$; if $H_{\rm tail} = 15 \,\text{nT}$, then $E_{\rm kc} = 37 \pm 2 \,\text{MeV}$.


Fig. 6.78 Noon-midnight cut-through model magnetosphere with projected orbits of low-velocity protons that arrive vertically at $\lambda_o = 67.8^{\circ}$ (L = 7) at midnight (According to Williams and Mead, 1965) and trajectories of protons with energies 5, 7, 10, 20, 30, and 40 MeV (According to Gall et al., 1968), vertically incident at Kiruna

Table 6.10 shows the coordinates of the points where protons of various energies, which are vertically incident at Kiruna at noon or midnight, enter the magnetosphere. The distance of the entrance region in the tail of the magnetosphere has been taken equal to $25 r_{\rm E}$ and the field in the tail $H_{\rm tail} = 40$ nT. In Table 6.17.1 λ is latitude, and ψ is longitude west of Kiruna.

The corresponding asymptotic directions of particles incident at Kiruna in vertical direction also depend on local time and are given in Table 6.11.

The geomagnetic cutoff rigidities computed by Gall and Jimenez (1967) for vertically incident particles as a function of geomagnetic latitude with due account of the influence of the magnetospheric tail on the trajectories are shown in Fig. 6.79. In curve a (dayside), and curve b (nightside) only particles entering the magnetosphere from the direction of the tail are considered. For comparison, cutoff rigidities are given for particles incident on the dayside coming from the dayside of the magnetosphere (curve c) and cutoff rigidities for the dipole approximation (curve d).

$E_{\rm k}$	Arrival at noon			Arriv	al at mid	midnight	
(MeV)	$r/r_{\rm E}$	Λ	Ψ	$r/r_{\rm E}$	Λ	Ψ	
5,000	10.8	13.3	27.3	25.0	-2.7	11/1	
300	10.9	4.1	33.6	25.0	-8.8	8.9	
250	11.0	-0.2	38.2	25.0	-10.2	8.7	
80	25.0	-13.7	147.8	25.0	-11.4	9.0	
60	25.0	-14.6	181.2	25.0	-11.0	7.2	
50	14.6	-7.6	258.1	25.0	-11.5	5.8	
40				25.0	-13.7	4.0	
30				25.0	-17.5	5.7	
20				25.0	-14.4	10.0	
10				25.0	-15.6	10.0	
7				25.0	15.4	11.1	
5				25.0	15.2	20.5	

 Table 6.10 Entrance points into the magnetosphere for protons which vertically arrive at Kiruna (According to Gall et al., 1968)

Table 6.11 Asymptotic directions of particles incident at Kiruna (A – asymptotic latitude, Ψ – asymptotic longitude, west of Kiruna) (According to Gall et al., 1968)

$E_{\rm k}$	No	Noon		Midnight		
(MeV)	Λ	Ψ	Λ	Ψ		
500	-8.4	59.1	-18.4	-11.1		
300	-21.5	81.4	-23.9	-5.6		
250	-25.5	96.3	-24.3	-4.1		

We may conclude that direct trajectory computations taking the influence of the magnetospheric tail into account make it possible to understand many properties of the asymptotic directions and behavior of low-energy cosmic ray cutoff at high latitudes.

6.18 Discriminating CR Magnetospheric Variations from Observed CR Data by the Spectrographical Method

6.18.1 The Matter of Problem

Observed inside the earth's atmosphere on the level $h_o(t)$, any component *i* of CR intensity variations at any point on the earth with cutoff rigidity $R_c(t)$ contains, in principle, all three possible classes of CR variations (atmospheric origin, magnetospheric origin, and extraterrestrial origin):



Fig. 6.79 Latitude dependence of the proton cutoff energy, a - midnight incidence from the magnetospheric tail; <math>b - noon incidence from tail; c - noon incidence from dayside of magnetosphere; d - dipole approximation (From Gall and Jimenez, 1967)

$$\Delta N_{i}(R_{c}(t), h_{o}(t), t) / N_{io} = \int_{R_{co}}^{\infty} \frac{\Delta m_{i}(R, h_{o}(t), g(t), T(h, t), E(h, t))}{m_{io}} W_{i}(R_{co}, R) dR$$
$$-\Delta R_{c}(t) W_{i}(R_{co}, R_{co}) + \int_{R_{co}}^{\infty} \frac{\Delta D(R, t)}{D_{o}(R)} W_{i}(R_{co}, R) dR,$$
(6.70)

where R_{co} is the cutoff rigidity at t = 0, and

$$W_{i}(R_{co}, R) = D_{o}(R) m_{io}(R, h_{oo}, g_{o}, T_{o}(h), E_{o}(h)) / N_{io}$$
(6.71)

is the coupling function between secondary CR of type *i* and primary CR, $D_o(R)$ is the differential CR rigidity spectrum outside of the atmosphere at t = 0, and $m_{io}(R, h_{oo}, g_o, T_o(h), E_o(h))$ is the integral multiplicity, which depends from primary particle rigidity *R*, pressure h_{oo} on the point of observation, gravitational acceleration g_o , vertical distributions of air temperature $T_o(h)$, and atmospheric electric field $E_o(h)$ (the index *o* means that all these values are taken at t = 0).

The first term on the right-hand side of Eq. 6.70 reflects CR time variations of atmospheric origin (meteorological effects). The second term is of geomagnetic origin, caused by secular variations of the main geomagnetic field connected with processes in the earth's interior, as well as with changes of electric currents in the earth's magnetosphere, especially in periods of geomagnetic storms. The third term

reflects CR variations of extraterrestrial origin, such as the generation of CRs in the sun's atmosphere and in the heliosphere, interplanetary modulation of galactic CRs, and interstellar CR variations. The atmospheric CR variations are considered in detail in Chapters 5–9 in Dorman, M2004). Geomagnetic variations are considered in this Chapter, and the part of extraterrestrial CR variations caused by processes in the heliosphere, in (Dorman, M1957, M1963a, b, M1975a, b).

In the first approximation the spectrum of primary CR variation can be described as

$$\Delta D(R,t) / D_o(R) = b(t) R^{-\gamma(t)}, \qquad (6.72)$$

where $\Delta D(R,t) = D(R,t) - D_o(R)$, and $D_o(R)$ is the differential spectrum of galactic CR at t = 0 (for which coupling functions are defined).

For magnetically disturbed periods the observed CR variation of some component i will be described by

$$\Delta N_{i}(R_{c},t) / N_{io} = -\Delta R_{c}(t) W_{i}(R_{co},R_{co}) + b(t) F_{i}(R_{co},\gamma(t)), \qquad (6.73)$$

where

$$\Delta N_{i}(R_{c},t) = N_{i}(R_{c},t) - N_{io}, N_{io} \equiv N_{io}(R_{co},0); \Delta R_{c}(t) = R_{c}(t) - R_{co}, \quad (6.74)$$

and

$$F_{i}(R_{co},\gamma(t)) = a_{i}k_{i}\left(1 - \exp\left(-a_{i}R_{co}^{-k_{i}}\right)\right)^{-1}\int_{R_{co}}^{\infty} R^{-(k_{i}+1+\gamma(t))}\exp\left(-a_{i}R^{-k_{i}}\right) \mathrm{d}R.$$
(6.75)

Here $\Delta R_c(t)$ is the change of cutoff rigidity owed to the change of the earth's magnetic field, and $W_i(R_{co}, R_{co})$ is determined by Eq. 3.134 at $R = R_{co}$. We use here the analytic approximation for the coupling function. It was introduced by Dorman (1969), who assumed that the polar (at $R_{co} = 0$) normalized coupling function for any secondary component of type i ($i = h\mu$ – for hard muons, $i = s\mu$ – for soft muons, i = ep – for the electron-photon component, i = n – for the total neutron component, i = m – for neutron multiplicities m = 1, 2, 3, ..., and so on) can be approximated by the special function (called the Dorman function in scientific literature):

$$W_{oi}(R,h_o) = a_i(h_o) k_i(h_o) R^{-(k_i(h_o)+1)} \exp\left(-a_i(h_o) R^{-k_i(h_o)}\right).$$
(6.76)

It is easy to see, that for any values of $a_i(h_o), k_i(h_o)$,

$$\int_{0}^{\infty} W_{oi}(R,h_o) \, \mathrm{d}R = \int_{0}^{\infty} a_i k_i R^{-(k_i+1)} \exp\left(-a_i R^{-k_i}\right) \mathrm{d}R = 1.$$
(6.77)

The normalized coupling functions at any point on earth with cutoff rigidity R_c will be

$$W_{i}(R_{co}, R, h_{o}) = \begin{cases} 0 & \text{if } R < R_{co} \\ a_{i}k_{i}R^{-(k_{i}+1)} \left(1 - a_{i}R_{co}^{-k_{i}}\right)^{-1} \exp\left(-a_{i}R^{-k_{i}}\right) & \text{if } R \ge R_{co}. \end{cases}$$
(6.78)

The coupling functions in the analytical approximation described by Eqs. 6.76 and 6.79, have the following important properties: (1) at large values of R, when $a_i R^{-k_i} \ll 1$, we obtain $W_i(R_{co}, R) \propto R^{-(k_i+1)}$, in good agreement with the observed data on the power-law differential rigidity spectrum of primary CRs and power-law increase of integral multiplicity with R (let us remember that according to Eq. 6.71 the coupling function is proportional to the product of the primary CR spectrum and integral multiplicity); (2) at very small values of R, when $a_i R^{-k_i} \gg 1$, we obtain a rapid decrease of $W_i(R_{co}, R)$ with decreasing R, which is in good agreement with the observed data from CR latitude surveys (plateau at small R_c ; see Chapters 4 and 5).

In Eq. 6.73 we have three unknown variables $\gamma(t)$, b(t), and $\Delta R_c(t)$, and for their determination we need data from at least three different components i = l, m, and n. For solving this inverse problem several versions of spectrographic method were developed: based on observation data of only single CR observatory, on two CR observatories with different cutoff rigidities, and on many CR observatories (Dorman, M1975b, M2004).

6.18.2 Determining Cutoff Rigidity Change by the Spectrographic Method on the Basis of Single CR Observatory Data

If we have observational data of some single CR observatory with cutoff rigidity R_{co} at t = 0, we need data for at least three different components i = l, m, and n to determine three unknown variables $\gamma(t)$, b(t), and $\Delta R_c(t)$. To solve this inverse problem let us consider the system of three equations of type Eq. 6.73. In accordance with Dorman,(M1975b, M2004), let us introduce the function

$$\Psi_{lmn}(R_{co},\gamma) = \frac{W_l F_m(R_{co},\gamma) - W_m F_l(R_{co},\gamma)}{W_m F_n(R_{co},\gamma) - W_n F_m(R_{co},\gamma)},$$
(6.79)

where

$$W_{l} \equiv W_{l}(R_{co}, R_{co}), \ W_{m} \equiv W_{m}(R_{co}, R_{co}), \ W_{n} \equiv W_{n}(R_{co}, R_{co}).$$
(6.80)

Then from

$$\Psi_{lmn}(R_{co},\gamma) = \frac{W_{l}\Delta N_{m}(R_{co},t) / N_{mo} - W_{m}\Delta N_{l}(R_{co},t) / N_{lo}}{W_{m}\Delta N_{n}(R_{co},t) / N_{no} - W_{n}\Delta N_{m}(R_{co},t) / N_{mo}},$$
(6.81)

the value of $\gamma(t)$ can be determined. For the solution of Eq. 6.81 let us take into account that function $\Psi_{lmn}(R_{co}, \gamma)$ determined by Eq. 6.79 is gradual function from parameter γ , and in the vicinity of some $\bar{\gamma}$ (determined by the type of CR variation: for Forbush decrease and CR solar cycle variations $\bar{\gamma} \approx 1$, for solar energetic particle events $\bar{\gamma} \approx 3$, and so on) we obtain in the first approximation,

$$\Psi_{lmn}\left(R_{co},\gamma\right) \approx \Psi_{lmn}\left(R_{co},\bar{\gamma}\right) + \left(\gamma - \bar{\gamma}\right) \left. \frac{\partial \Psi_{lmn}\left(R_{co},\gamma\right)}{\partial \gamma} \right|_{\gamma \to \bar{\gamma}} \tag{6.82}$$

or in the second approximation

$$\begin{split} \Psi_{lmn}\left(R_{co},\gamma\right) &\approx \Psi_{lmn}\left(R_{co},\bar{\gamma}\right) + \left(\gamma - \bar{\gamma}\right) \left. \frac{\partial \Psi_{lmn}\left(R_{co},\gamma\right)}{\partial\gamma} \right|_{\gamma \to \bar{\gamma}} \\ &+ \left(\gamma - \bar{\gamma}\right)^2 \left. \frac{\partial^2 \Psi_{lmn}\left(R_{co},\gamma\right)}{2!\partial\gamma^2} \right|_{\gamma \to \bar{\gamma}}. \end{split}$$
(6.83)

By introducing Eq. 6.82 or Eq. 6.83 into Eq. 6.81, we determine parameter $\gamma(t)$. Using the found value of $\gamma(t)$ in dependence of time *t*, we determine

$$\Delta R_{\rm c}(t) = \frac{F_l(R_{\rm co},\gamma(t))\Delta N_m(R_{\rm c},t)/N_{mo} - F_m(R_{\rm co},\gamma(t))\Delta N_l(R_{\rm c},t)/N_{lo}}{F_m(R_{\rm co},\gamma(t))\Delta N_n(R_{\rm c},t)/N_{no} - F_n(R_{\rm co},\gamma(t))\Delta N_m(R_{\rm c},t)/N_{mo}}$$
(6.84)

and

$$b(t) = \frac{W_l \Delta N_m(R_c, t) / N_{mo} - W_m \Delta N_l(R_c, t) / N_{lo}}{W_l F_m(R_{co}, \gamma(t)) - W_m F_l(R_{co}, \gamma(t))}.$$
(6.85)

So in magnetically disturbed periods, the rigidity spectrum of primary CR variation at the top of the atmosphere and cutoff rigidity change can be determined in dependence of time t. Let us note that the early versions of the spectrographic method for single observatory started to develop about 40 years ago (Dorman et al., 1968, 1971, 1973a, b; Dorman and Sergeev, 1969, 1970; Dvornikov et al. 1972; Dorman and Shkhalakhov, M1975a, b).

6.18.3 Determining the Cutoff Rigidity Changes by the Spectrographic Method on the Basis of Data from Two CR Observatories (Case One and Three Components)

In this case for the spectrum described by Eq. 6.70 we have four unknown variables: $\Delta R_{c1}(t), \Delta R_{c2}(t), b(t), \gamma(t)$. This means that for solving the inverse problem and to determine the changes of cutoff rigidities on both CR observatories, we need at least four sets of CR data with different coupling functions. Let us first consider the case of one CR component in the first observatory with cutoff rigidity R_{c1} and three components in the second observatory with cutoff R_{c2} . The system of equations for determining $\Delta R_{c1}(t), \Delta R_{c2}(t), b(t), \gamma(t)$ will be

$$\Delta N_k (R_{c1}, t) / N_{ko} = -\Delta R_{c1} (t) W_k (R_{c1}, R_{c1}) + b (t) F_k (R_{c1}, \gamma(t)), \qquad (6.86)$$

$$\Delta N_l(R_{c2},t) / N_{lo} = -\Delta R_{c2}(t) W_l(R_{c2},R_{c2}) + b(t) F_l(R_{c2},\gamma(t)), \qquad (6.87)$$

$$\Delta N_m(R_{c2},t) / N_{mo} = -\Delta R_{c2}(t) W_m(R_{c2},R_{c2}) + b(t) F_m(R_{c2},\gamma(t)), \qquad (6.88)$$

$$\Delta N_n(R_{c2},t) / N_{no} = -\Delta R_{c2}(t) W_n(R_{c2},R_{c2}) + b(t) F_n(R_{c2},\gamma(t)).$$
(6.89)

In this case we start by determining from Eqs. 6.87–6.89 $\gamma(t)$, b(t), and $\Delta R_{c2}(t)$ by the same manner as in Section 6.18.2, and then determine $\Delta R_{c1}(t)$ from Eq. 6.86. So, there are four steps in solving the inverse problem.

1. We calculate for this set of CR detectors the special function:

$$\Psi_{lmn}(R_{c2o},\gamma) = \frac{W_l F_m(R_{c2o},\gamma) - W_m F_l(R_{c2o},\gamma)}{W_m F_n(R_{c2o},\gamma) - W_n F_m(R_{c2o},\gamma)},$$
(6.90)

where

$$W_{l2} \equiv W_l \left(R_{c2o}, R_{c2o} \right), \ W_{m2} \equiv W_m \left(R_{c2o}, R_{c2o} \right), \ W_{n2} \equiv W_n \left(R_{c2o}, R_{c2o} \right).$$
(6.91)

2. We determine from the equation

$$\Psi_{lmn}(R_{c2},\gamma(t)) = \frac{W_{l2}\Delta N_m(R_{c2},t) / N_{mo} - W_{m2}\Delta N_l(R_{c2},t) / N_{lo}}{W_{m2}\Delta N_n(R_{c2},t) / N_{no} - W_{n2}\Delta N_m(R_{c2},t) / N_{mo}},$$
(6.92)

the value of $\gamma(t)$ (the method described in Section 6.18.2 for solving Eq. 6.81 can be used).

3. Using the values of $\gamma(t)$ found from Eq. 6.92 for each time t, we determine

$$\Delta R_{c2}(t) = \frac{F_l(R_{c2o}, \gamma(t)) \Delta N_m(R_{c2}, t) / N_{mo} - F_m(R_{c2o}, \gamma(t)) \Delta N_l(R_{c2}, t) / N_{lo}}{F_m(R_{c2o}, \gamma(t)) \Delta N_n(R_{c2}, t) / N_{no} - F_n(R_{c2o}, \gamma(t)) \Delta N_m(R_{c2}, t) / N_{mo}},$$
(6.93)

$$b(t) = \frac{W_{l2}\Delta N_m(R_{c2},t) / N_{mo} - W_{m2}\Delta N_l(R_{c2},t) / N_{lo}}{W_{l2}F_m(R_{c2o},\gamma(t)) - W_{m2}F_l(R_{c2o},\gamma(t))}.$$
(6.94)

4. From Eq. 6.86 we then determine

$$\Delta R_{c1}(t) = [b(t) F_k(R_{c1o}, \gamma(t)) - \Delta N_k(R_{c1}, t) / N_{ko}] W_{k1}, \qquad (6.95)$$

where $W_{k1} \equiv W_{k1} (R_{c1o}, R_{c1o})$.

6.18.4 Determining the Cutoff Rigidity Changes in the Case of Two Components in the Each of the Two CR Observatories

If there are two and two components in both CR Observatories, instead of the system Eqs. 6.86–6.89 we will have

$$\Delta N_k (R_{c1}, t) / N_{ko} = -\Delta R_{c1} (t) W_k (R_{c1o}, R_{c1o}) + b (t) F_k (R_{c1o}, \gamma(t)), \qquad (6.96)$$

$$\Delta N_{l}(R_{c1},t) / N_{lo} = -\Delta R_{c1}(t) W_{l}(R_{c1o},R_{c1o}) + b(t) F_{l}(R_{c1o},\gamma(t)), \qquad (6.97)$$

$$\Delta N_m (R_{c2}, t) / N_{mo} = -\Delta R_{c2} (t) W_m (R_{c2o}, R_{c2o}) + b(t) F_m (R_{c2o}, \gamma(t)), \qquad (6.98)$$

$$\Delta N_n(R_{c2},t) / N_{no} = -\Delta R_{c2}(t) W_n(R_{c2o}, R_{c2o}) + b(t) F_n(R_{c2o}, \gamma(t)).$$
(6.99)

From the system of Eqs. 6.96–6.99 we exclude the linear unknown variables b(t), $\Delta R_{c1}(t)$, $\Delta R_{c2}(t)$ and finally obtain a nonlinear equation for determining $\gamma(t)$:

$$\frac{W_k \Delta N_l (R_{c1}, t) / N_{lo} - W_l \Delta N_k (R_{c1}, t) / N_{ko}}{W_m \Delta N_n (R_{c2}, t) / N_{no} - W_n \Delta N_m (R_{c2}, t) / N_{mo}} = \Psi_{klmn} (R_{c1o}, R_{c2o}, \gamma(t)), \quad (6.100)$$

where the special function for combination of two CR observatories is determined by

$$\Psi_{klmn}(R_{c1o}, R_{c2o}, \gamma) = \frac{W_{k1}F_l(R_{c1o}, \gamma) - W_{l1}F_k(R_{c1o}, \gamma)}{W_{m2}F_n(R_{c2o}, \gamma) - W_{n2}F_m(R_{c2o}, \gamma)},$$
(6.101)

which can be calculated for any pair of CR observatories by using the known functions $F_k(R_{c1o},\gamma), F_l(R_{c1o},\gamma), F_m(R_{c2o},\gamma), F_n(R_{c2o},\gamma)$, and known values $W_{k1} \equiv W_k(R_{c1o}, R_{c1o}), W_{l1} \equiv W_l(R_{c1o}, R_{c1o}), W_{m2} \equiv W_m(R_{c2o}, R_{c2o})$, and $W_{n2} \equiv W_n(R_{c2o}, R_{c2o})$. After determining $\gamma(t)$, we can determine the other three unknown variables:

$$\Delta R_{c1}(t) = \frac{F_k(R_{c1o}, \gamma(t)) \Delta N_l(R_{c1}, t) / N_{lo} - F_l(R_{c1o}, \gamma(t)) \Delta N_k(R_{c1}, t) / N_{ko}}{W_{k1} F_l(R_{c1o}, \gamma(t)) - W_{l1} F_k(R_{c1o}, \gamma(t))}$$
(6.102)

$$\Delta R_{c2}(t) = \frac{F_m(R_{c2o}, \gamma(t))\Delta N_n(R_{c2}, t) / N_{no} - F_n(R_{c2o}, \gamma(t))\Delta N_m(R_{c2}, t) / N_{mo}}{W_{m2}F_n(R_{c2o}, \gamma(t)) - W_{n2}F_m(R_{c2o}, \gamma(t))},$$
(6.103)
$$W_{k1}\Delta N_l(R_{c1}, t) / N_{lo} - W_{l1}\Delta N_k(R_{c1}, t) / N_{ko}$$

$$b(t) = \frac{W_{k1} - V(t_{c1}, \gamma) + V_{k0} - W_{11} - V(t_{c1}, \gamma) + V_{k0}}{W_{k1} F_l(R_{c1o}, \gamma(t)) - W_{l1} F_k(R_{c1o}, \gamma(t))}$$

$$= \frac{W_{m2} \Delta N_n(R_{c2}, t) / N_{no} - W_n \Delta N_m(R_{c2}, t) / N_{mo}}{W_{m2} F_n(R_{c2o}, \gamma(t)) - W_{n2} F_m(R_{c2o}, \gamma(t))}.$$
(6.104)

6.18.5 Determining Planetary Cutoff Rigidity Changes Distribution on the Basis of Many CR Observatories' Data by the Spectrographic Method

Let us suppose that we have CR data from *n* CR observatories of the worldwide network with cutoff rigidities R_{c1o} , R_{c2o} , R_{c3o} ,..., R_{cno} at t = 0. In this case we will have unknown variables $\Delta R_{c1}(t)$, $\Delta R_{c2}(t)$, $\Delta R_{c3}(t)$,..., $\Delta R_{cn}(t)$, b(t), and $\gamma(t)$, i.e., n + 2 unknown variables. It means that, for solving the inverse problem, and by CR data to determine the planetary cutoff rigidity changes distribution, we need at least CR data of n + 2 detectors. Let us consider two cases. Case 1. Let us suppose that at one of the CR observatories (e.g., observatory 1) there are measurements of three CR components k, l, and m with different coupling functions. In this case the system of n + 2 equations will be

$$\Delta N_k(R_{c1},t) / N_{ko} = -\Delta R_{c1}(t) W_{k1} + b(t) F_k(R_{c1o},\gamma(t)), \qquad (6.105)$$

$$\Delta N_{l}(R_{c1},t) / N_{lo} = -\Delta R_{c1}(t) W_{l1} + b(t) F_{l}(R_{c1o},\gamma(t)), \qquad (6.106)$$

$$\Delta N_m(R_{c1},t) / N_{mo} = -\Delta R_{c1}(t) W_{m1} + b(t) F_m(R_{c1o},\gamma(t)), \qquad (6.107)$$

$$\Delta N_2(R_{c2},t) / N_{2o} = -\Delta R_{c2}(t) W_2 + b(t) F_2(R_{c2o},\gamma(t)), \qquad (6.108)$$

$$\Delta N_3(R_{c3},t) / N_{3o} = -\Delta R_{c3}(t) W_3 + b(t) F_3(R_{c3o},\gamma(t)), \qquad (6.109)$$

$$\Delta N_n(R_{\rm cn},t) / N_{no} = -\Delta R_{\rm cn}(t) W_n + b(t) F_n(R_{\rm cno},\gamma(t)), \qquad (6.110)$$

where

$$W_{k1} \equiv W_k (R_{c1o}, R_{c1o}), W_{l1} \equiv W_l (R_{c1o}, R_{c1o}), W_{m1} \equiv W_m (R_{c1o}, R_{c1o}), W_2 \equiv W_2 (R_{c2o}, R_{c2o}), W_3 \equiv W_3 (R_{c3o}, R_{c3o}), \dots W_n \equiv W_n (R_{cno}, R_{cno}).$$
(6.111)

From Eqs. 6.105–6.107 we determine $\gamma(t)$, $\Delta R_{c1}(t)$, and b(t) as was done in Section 6.18.2. In the first, we calculate the special function

$$\Psi_{klm}(R_{c1o},\gamma) = \frac{W_{k1}F_l(R_{c1o},\gamma) - W_{l1}F_k(R_{c1o},\gamma)}{W_{l1}F_m(R_{c1o},\gamma) - W_{m1}F_l(R_{c1o},\gamma)},$$
(6.112)

and then determine $\gamma(t)$ from the equation

$$\Psi_{klm}(R_{c1o},\gamma(t)) = \frac{W_{k1}\Delta N_l(R_{c1o},t)/N_{lo} - W_{l1}\Delta N_k(R_{c1o},t)/N_{ko}}{W_{l1}\Delta N_m(R_{c1o},t)/N_{mo} - W_{m1}\Delta N_l(R_{c1o},t)/N_{lo}}.$$
(6.113)

After determining $\gamma(t)$, we determine

$$\Delta R_{c1}(t) = \frac{F_k(R_{c1o}, \gamma(t)) \Delta N_l(R_{c1}, t) / N_{lo} - F_l(R_{c1o}, \gamma(t)) \Delta N_k(R_{c1}, t) / N_{ko}}{F_l(R_{c1o}, \gamma(t)) \Delta N_m(R_{c1}, t) / N_{mo} - F_m(R_{c1o}, \gamma(t)) \Delta N_l(R_{c1}, t) / N_{lo}},$$
(6.114)

and

$$b(t) = \frac{W_{k1}\Delta N_l(R_{c1},t)/N_{lo} - W_{l1}\Delta N_k(R_{c1},t)/N_{ko}}{W_{k1}F_l(R_{c1o},\gamma(t)) - W_{l1}F_k(R_{c1o},\gamma(t))}.$$
(6.115)

Now we can easily determine the changes of cutoff rigidities on all other CR observatories:

$$\Delta R_{c2}(t) = [b(t)F_2(R_{c2o},\gamma(t)) - \Delta N_2(R_{c2},t)/N_{2o}]/W_2, \qquad (6.116)$$

$$\Delta R_{c3}(t) = [b(t)F_3(R_{c3o},\gamma(t)) - \Delta N_3(R_{c3},t)/N_{3o}]/W_3, \qquad (6.117)$$

$$\Delta R_{cn}(t) = [b(t)F_n(R_{cno},\gamma(t)) - \Delta N_n(R_{cn},t)/N_{no}]/W_n, \qquad (6.118)$$

Case 2. Let us suppose that at two of the CR observatories (e.g., observatories 1 and 2) there are measurements of two CR components at each of these observatories: k, l, and m, p. In this case, the system of n + 2 equations will be

$$\Delta N_k(R_{c1},t) / N_{ko} = -\Delta R_{c1}(t) W_{k1} + b(t) F_k(R_{c1o},\gamma(t)), \qquad (6.119)$$

$$\Delta N_{l}(R_{c1},t) / N_{lo} = -\Delta R_{c1}(t) W_{l1} + b(t) F_{l}(R_{c1o},\gamma(t)), \qquad (6.120)$$

$$\Delta N_m(R_{c2},t) / N_{mo} = -\Delta R_{c2}(t) W_{m2} + b(t) F_m(R_{c2o},\gamma(t)), \qquad (6.121)$$

$$\Delta N_{p}(R_{c2},t) / N_{po} = -\Delta R_{c2}(t) W_{p2} + b(t) F_{p}(R_{c2o},\gamma(t)), \qquad (6.122)$$

$$\Delta N_3(R_{c3,t}) / N_{3o} = -\Delta R_{c3}(t) W_3 + b(t) F_3(R_{c3o}, \gamma(t)), \qquad (6.123)$$

$$\Delta N_n(R_{cn},t) / N_{no} = -\Delta R_{cn}(t) W_n + b(t) F_n(R_{cno},\gamma(t)), \qquad (6.124)$$

where

$$W_{k1} \equiv W_k(R_{c1o}, R_{c1o}), W_{l1} \equiv W_l(R_{c1o}, R_{c1o}), W_{m2} \equiv W_m(R_{c2o}, R_{c2o}), W_{p2} \equiv W_p(R_{c2o}, R_{c2o}), W_3 \equiv W_3(R_{c3o}, R_{c3o}), \dots, W_n \equiv W_n(R_{cno}, R_{cno}).$$
(6.125)

From Eqs. 6.119–6.122, we determine $\gamma(t)$, $\Delta R_{c1}(t)$, $\Delta R_{c2}(t)$, and b(t), as was done in Section 6.18.4. In the first, we calculate the special function

$$\Psi_{klmp}(R_{c1o}, R_{c2o}, \gamma) = \frac{W_{k1}F_l(R_{c1o}, \gamma) - W_{l1}F_k(R_{c1o}, \gamma)}{W_{m2}F_p(R_{c2o}, \gamma) - W_{p2}F_m(R_{c2o}, \gamma)},$$
(6.126)

and then from the equation

$$\frac{W_{k1}\Delta N_l(R_{c1},t)/N_{lo} - W_{l1}\Delta N_k(R_{c1},t)/N_{ko}}{W_{m2}\Delta N_p(R_{c2},t)/N_{po} - W_{p2}\Delta N_m(R_{c2},t)/N_{mo}} = \Psi_{klmp}(R_{c1o}, R_{c2o}, \gamma(t)), \quad (6.127)$$

we determine $\gamma(t)$. After we determine $\Delta R_{c1}(t)$, $\Delta R_{c2}(t)$, and b(t):

$$\Delta R_{c1}(t) = \frac{F_k(R_{c1o}, \gamma(t)) \Delta N_l(R_{c1}, t) / N_{lo} - F_l(R_{c1o}, \gamma(t)) \Delta N_k(R_{c1}, t) / N_{ko}}{W_{k1}F_l(R_{c1o}, \gamma(t)) - W_{l1}F_k(R_{c1o}, \gamma(t))},$$
(6.128)

$$\Delta R_{c2}(t) = \frac{F_m(R_{c2o}, \gamma(t)) \Delta N_p(R_{c2}, t) / N_{po} - F_p(R_{c2o}, \gamma(t)) \Delta N_m(R_{c2}, t) / N_{mo}}{W_{m2}F_n(R_{c2o}, \gamma(t)) - W_{p2}F_m(R_{c2o}, \gamma(t))},$$
(6.129)

$$b(t) = \frac{W_{k1}\Delta N_l(R_{c1},t) / N_{lo} - W_{l1}\Delta N_k(R_{c1},t) / N_{ko}}{W_{k1}F_l(R_{c1o},\gamma(t)) - W_{l1}F_k(R_{c1o},\gamma(t))}$$

$$= \frac{W_{m2}\Delta N_p(R_{c2},t) / N_{po} - W_{p2}\Delta N_m(R_{c2},t) / N_{mo}}{W_{m2}F_p(R_{c2o},\gamma(t)) - W_{p2}F_m(R_{c2o},\gamma(t))}.$$
(6.130)

Now we can easily determine the changes of cutoff rigidities at all other CR observatories from 3 to *n*:

$$\Delta R_{c3}(t) = [b(t)F_3(R_{c3o},\gamma(t)) - \Delta N_3(R_{c3},t)/N_{3o}]/W_3, \qquad (6.131)$$

$$\Delta R_{cn}(t) = \left[b(t) F_n(R_{cno}, \gamma(t)) - \Delta N_n(R_{cn}, t) / N_{no} \right] / W_n, \qquad (6.132)$$

Let us remember that $\Delta N_n (R_{cn}, t) / N_{no}$ are observed on the *n*th observatory CR intensity variation, functions $F_n (R_{cno}, \gamma(t))$ were determined by Eq. 6.75, and values W_n – by Eq. 6.125.

6.18.6 An Example of Using the Spectrographic Method for Determining CR Geomagnetic Variations; Application to Ring Current (Events in May and June 1972)

In Dorman et al. (1973a), the Irkutsk spectrograph data ($R_{co} = 3.8 \,\text{GV}$) are used for studying in detail two cases of CR Forbush decreases in May and June 1972. Table 6.12 classifies the information on solar chromospheric flares which may have caused the discussed events.

Observed CR variations and results of spectrographic analysis are shown in Fig. 6.80 for the event in May 1972 and in Fig. 6.81 for the event in June 1972. Panels a in both figures present the initial experimental data on the hard muon component measured at sea level (thick solid curve) and neutron component measured at sea level (thin solid curve) and at altitudes of 2,000 m (dashed line) and 3,000 m (dotted line). Panels b in both figures present the magnetospheric disturbances represented with the D_{st} -variation), panels c show determined values of ΔR_c , and panels d – parameter γ , panels e represent extraterrestrial variation of primary CR spectrum $\Delta D(R)/D_o(R)$ for particles with rigidity 4.5 GV and 15 GV, panels f and g show magnetospheric and interplanetary variations of the neutron component at sea level.

Comparison of the D_{st} -variation behavior in May and June, 1972 shows that the magnetospheric disturbances were different during these periods, both in character and value. In the May event, the D_{st} -disturbances did not exceed 25 nT whereas in the June event a magnetic storm with a field depression of ~200 nT was detected. The change in the geomagnetic cutoff rigidity displays a similar difference.

Table 6.12 Characteristics of phenomena connected with Forbush effects in May and June 1972(From Dorman et al., 1973a)

Chromospheric flares				Forbush decrease				
Date	t _{max}	Duration (min)	Class	Coordinates	Start (UT) (%)	$\Delta N/N$	Г	$\Delta R_c(\text{GV})$
May 28 June 15	13 h 30 m 9 h 54 m	220 60	2B 2N	9 N, 30 E 12 S, 10 E	May 30, ~12 h June 17, 14 h	-3.9 -6.0	-1.0 -1.5	$0 \pm 0.2 \\ -0.5 \pm 0.2$



The observed changes in R_c were very small in May but reached a value of 1.5 ± 0.2 GV in June. This comparison provokes a conclusion about a persistent relationship between the magnetospheric disturbances characterized by the D_{st} -index and the changes in the CR magnetic cutoff ΔR_c .

This conclusion was verified by analyzing a number of Forbush effects accompanied by magnetic disturbances. The results of the analysis are presented in Table 6.13. A comparison between D_{st} and ΔR_c shows that these values fail to exhibit an unambiguous relationship (i.e., a disturbance in D_{st} does not always involve a ΔR_c effect). This conclusion does not contradict theoretical results considered above, in Sections 6.14–6.15. The modern ideas imply that the storm-time D_{st} -variation is mainly due to the changes of the conditions in the magnetospheric westward current system. The ΔR_c effect is a function of the total current intensity and spatial distribution of the current density in this current system. Therefore, a change in the CR geomagnetic cutoff is a function of some parameters determining the conditions and geometry of the current system. This current system may be considered in the first approximation as the ring current, and the results obtained for



Fig. 6.81 The same as in Fig. 6.80, but for the Forbush effect in June, 1972 (From Dorman et al., 1973a)

 $\Delta R_{\rm c}$ may be used together with the $D_{\rm st}$ -data to estimate the total current intensity in the ring as well as the effective radius of the ring current (see Table 6.13).

Of course, the current structure is more complex. The current exhibits a certain distribution in the radiation belts; and a detailed analysis of the planetary distribution of D_{st} and ΔR_c in combination with a comparison to theoretical calculations for the corresponding models of the magnetospheric spatial currents are necessary to obtain the complete characteristics of the ring current.

Date of magnetic storm	Field depression (nT)	$\Delta R_c \text{ (GV)at} R_{co} = 3.8 \text{ GV}$	Current ring radius $(r_{\rm E})$	$M_{ m c}$ / $M_{ m E}$
November 7, 1970	100	-1.3 ± 0.3	5	0.5
January 21, 1971	70	-0.2 ± 0.3	9	0.65
June 18, 1972	180	-0.8 ± 0.2	5	0.4
August 4, 1972	123	0 ± 0.2	5	< 0.1
August 5, 1972	130	-1.3 ± 0.2	4	0.2
August 9, 1972	160	-0.8 ± 0.2	5	0.4

Table 6.13 Determining of ΔR_c and parameters of the current ring from the Irkutsk CR spectrograph data (From Dorman et al., 1973b)

6.19 Cutoff Rigidity Variations of European Mid-latitude Stations During the September 1974 Forbush Decrease

6.19.1 The Matter of Problem

Flückiger et al. (1975) noted that in studies of primary spectral variations during CR Forbush decreases based on NM data, one must account for perturbations in the geomagnetic field as a cause of considerable changes in cutoff rigidity. Possibilities for an experimental determination of cutoff variations have been examined by several authors. A review of the different techniques has been given in Debrunner et al. (1973), where a special method for mid-latitude stations was also proposed. Louis et al. (1972) represents a comprehensive study of variations in cutoff rigidity during magnetic storms. In Agrawal et al. (1974) it was suggested that during the complex of events in August 1972, a sudden increase in CR intensity coinciding with a geomagnetic storm with $D_{st} \approx 200$ nT on August 4, was caused by a lowering of the cutoff rigidity.

6.19.2 Used Data and Main Characteristics of the Event

In Flückiger et al. (1975) variations of the cutoff rigidity at Jungfraujoch during the September 1974 event are analyzed based on the hourly NM data of Kiel and Utrecht. All these stations have nearly the same asymptotic directions of viewing, which is a necessary condition for the used method of analysis. On September 13, 1974, a decrease in CR intensity started as indicated in Fig. 6.82. On September 15 at 13.43 UT, a storm sudden commencement (SSC) occurred, probably due to a complex of solar flares on September 13 starting between 14.58 and 15.13 UT in McMath regions 13224 and 13225 and was followed by a strong geomagnetic storm and sharp Forbush decrease at very high-latitude stations. However, for Kiel the intensity remained practically constant for several hours whereas at other mid-latitude stations (Utrecht, Dourbes, Zugspitze, Jungfraujoch, and Rome) an increase

Fig. 6.82 Relative variations of the total counting rates, with respect to the reference level of September 4–8, 1974, for the stations Rome (ROM), Jungfraujoch (JUN), Zugspitze (ZUG), Dourbes (DOU), Utrecht (UTR), Kiel (KIE), and Oulu (OUL) (From Flückiger et al., 1975)



in intensity was recorded. The intensity at Zugspitze and Jungfraujoch reached a maximum of +1.0% and +1.5%, respectively, relative to the average CR intensity of September 4–8, 1974, which was used as the reference level. As this observed intensity increase shows an "inverse" latitude effect, which is expected up to $R_c \approx 7 \,\text{GV}$ from theoretical considerations of cutoff changes, the only possible cause for this effect is a lowering of the geomagnetic cutoff rigidity. An increase due to energetic solar particles or an anisotropy would show a normal latitude effect and can therefore be excluded. Also on this basis, the behavior of the recordings from Kiel and the other mid-latitude stations can be explained. As the cutoff rigidity at Oulu is less than the atmospheric cutoff, this station records the true Forbush decrease.

6.19.3 Results of Data Analysis

According to Flückiger et al. (1975) during a Forbush decrease the primary cosmic ray spectrum D(R,t) is generally described by

$$D(R,t) = \left(1 + \eta(t)R^{-\gamma(t)}\right) D_o(R), \qquad (6.133)$$

where $D_o(R)$ is the undisturbed primary differential rigidity spectrum. Taking into account a possible simultaneous change of the effective cutoff rigidity R_c , the relative variations of the counting rate of any NM at atmospheric depth h are then given by

$$\Delta N(h, R_{\rm c}, t) / N_o = \int_{R_{\rm co} + \Delta R_{\rm c}(t)}^{\infty} D(R, t) W(h, R, R_{\rm co}) \,\mathrm{d}R, \qquad (6.134)$$

where D(R,t) is determined by Eq. 6.133. For September 1974, the normalized coupling functions $W(h, R, R_{co})$ have been deduced from the best-fit differential response functions. The exponent $\gamma(t)$ may vary from event to event (e.g., Lockwood, 1971) and even during an event (Aldagarova et al., 1973). Since nearly all experimentally obtained values for $\gamma(t)$ fall in the range $0 \le \gamma(t) \le 1.6$ with errors in the order of ± 0.4 , the exponent $\gamma(t)$ was varied in this analysis from 0.4 to 1.4 in steps of 0.2. For each $\gamma(t)$ the amplitudes $\eta(t)$ in Eq. 6.133 were determined for the stations Kiel and Utrecht. The spectra so obtained have been used to calculate the relative variations of the total counting rate at Jungfraujoch, $(\Delta N(h, R_c, t) / N_o)_{th}^{JJ}$, for $(\Delta R_{\rm c}(t))_{II} = 0$. The differences between observed and theoretical variations were attributed to cutoff changes. Numerical values for the variations $(\Delta R_{\rm c}(t))_{II}$ have then been determined. Taking into account the theoretical latitude dependence of $\Delta R_{\rm c}(t)$ according to Obayashi (1959), the cutoff changes $(\Delta R_{\rm c}(t))_{\rm K}$ of Kiel and $(\Delta R_{\rm c}(t))_{II}$ of Utrecht have been calculated from $(\Delta R_{\rm c}(t))_{II}$. The same computing process was then repeated using the changed cutoff rigidity for the three stations until the variation of the altered value of $(R_c)_{II}$ was less than 0.01 GV.

Figure 6.83 shows the resulting mean values of $(\Delta R_c(t))_{JJ}$ computed with $\gamma = 0.8$ for September 13–18, 1974. As a check the data from Oulu and Dourbes



Fig. 6.83 Variations of the cutoff rigidity at Jungfraujoch during September 13–18, 1974: dark line – deduced from the NM data of Kiel and Utrecht, points – calculated from D_{st} variation (From Flückiger et al., 1975)

was treated in the same way as the Kiel and Utrecht data. The results for the cutoff changes at Jungfraujoch are in close agreement with those obtained from Kiel and Utrecht measurements. As an additional check, the cutoff changes for Zugspitze and Rome were calculated with measurements from Oulu, Kiel, Utrecht, and Dourbes. These results show the expected latitude-dependence of the cutoff variations as compared with ΔR_c for Jungfraujoch.

For the determination of the accuracy in the deduced cutoff variations, we must account for errors in the coupling functions, inaccuracies in the exponent γ , statistical errors of the measured counting rates, as well as for the errors introduced by pressure corrections. A discussion on the reliability of this method has already been given in the paper of Debrunner et al. (1973). Following the same procedure, the relative errors in $(\Delta R_c (t))_{JJ}$ due to unreliability in the coupling functions have been determined to be in the order of $\pm 30\%$. The errors in γ cause a mean inaccuracy in the determination of cutoff variations of +0.10/-0.03 GV. The uncertainties due to inaccuracies in the NM data are of the order of ± 0.1 GV. Thus, the maximum error in $|(\Delta R_c (t))_{JJ}|$ given in Fig. 6.83 has the value of ± 0.3 GV.

6.19.4 Main Results and Discussion

Cutoff rigidity variations during a Forbush decrease are thought to be due mainly to a ring current with a magnetic moment opposite to the intrinsic geomagnetic moment. Therefore the obtained results are compared with cutoff changes following from hourly values of the index D_{st} , which are a measure for the ring current field near the earth (e.g., Akasofu, 1963). From the D_{st} values, it is also possible to deduce theoretical cutoff variations (e.g., Obayashi, 1959). These calculated values for the cutoff rigidity changes at Jungfraujoch are also given in Fig. 6.83. The comparison between the theoretical and experimentally deduced values of the variations of cutoff rigidity shows reasonably good agreement. Furthermore, there seems to be a maximum sensitivity in cutoff variations around 16.00 local time when the asymptotic directions for low rigidities are in the geomagnetic tail; this phenomenon was also observed in analysis of the July 1974 Forbush decrease. This has also been noticed by Hatton and Marsden (1962) and may be due to an asymmetric ring current, as pointed out by Yoshida et al. (1968). However, further research is needed for a better understanding of these effects.

Flückiger et al. (1975) came to the conclusion that during the September, 1974 event, the effective vertical cutoff rigidity of Jungfraujoch was considerably lowered with a maximum variation $(\Delta R_c(t))_{JJ} = -1.0 \pm 0.3 \text{ GV}$ between 15.00 and 19.00 UT on September 15. The magnitude of the changes are in reasonable agreement with the theoretical values calculated from D_{st} and with values for similar events cited in the literature (e.g., Freier, 1962; Hatton et al., 1962; Wolfson et al., 1967; Yoshida et al., 1968; Wolfson and Nobles, 1968, 1970).

6.20 The Extraterrestrial and Geomagnetic Variations in CR During the Forbush Decreases of March 26, 1976

6.20.1 Observation Data

The paper of Dorman et al. (1977) presents the results of the analysis of the CR intensity variations detected during the Forbush effect of March 26–28, 1976 with the help of the Sayans spectrographic complex (Irkutsk, $R_{co} = 3.81 \,\text{GV}$). The complex consists of three stations located at altitudes of 435, 2000, and 3,000 m above sea level. The stations are equipped with the standard NM-64 neutron super-monitors for detection of the CR secondary nucleonic component within a statistical accuracy of $\pm 0.1\%$ for 2-h intervals of measurements. The vertical muon component is additionally detected at the 435 m level with a Geiger-counter telescope within a statistical accuracy of $\pm 0.14\%$. The experimental data for the neutron and energetic meson components detected with the spectrographic complex from March 25 to 28, 1976 are shown in Fig. 6.84. It can be seen from the plots that a CR increase was observed on March 26 with the amplitude $\sim 3.8\%$ at the 435 m level, $\sim 6\%$ at the 3,000 m level in the neutron component and $\sim 0.3\%$ in the muon component. Such a relationship between the amplitudes is usually observed during the solar CR arrival to the earth. The experimental spectrographic data were processed using the spectrographic method (see Section 6.18).

The obtained results show that apart from the Forbush decrease, the variation of geomagnetic cutoff rigidity is very important (panel b in Fig. 6.84). The latter effect was so significant (panel c in Fig. 6.84) that it could not only compensate the Forbush decrease in the CR intensity but cause a total increase detected in the neutron components.

It can be seen from panel b in Fig. 6.84 that the variation $\Delta R_c(t)$ during the main phase of the magnetic storm reached $\approx 0.9 \,\text{GV}$ (at $R_{co} = 3.81 \,\text{GV}$). Figure 6.84 also presents the D_{st} -variations obtained from the ground-based magnetic observations. According to the D_{st} -data, a magnetic storm with a $\sim 225 \,\text{nT}$ depression of the field during the main phase was detected on March 26, 1976.

6.20.2 Comparison Between the $\Delta R_c(t)$ and D_{st} -Variations

The comparison between the $\Delta R_c(t)$ and D_{st} -variations show a similarity of their changes in time. This feature, however, cannot be an immediate confirmation of the reality of the found effect of the variation of the geomagnetic cutoff rigidity. There-fore the experimental data for the neutron component from the worldwide network of stations were examined (see Fig. 6.85): Tixie ($R_{co} = 0.53 \, GV$), Norilsk (0.63 GV), Yakutsk (1.0 GV), Novosibirsk (2.91 GV), Irkutsk (3.81 GV), Khabarovsk (5.54 GV), and Tokyo (11.61 GV).



Fig. 6.84 The results of the CR variation measurements by the Sayan spectrograph complex: **a** the data for the neutron (dashed line) and muon (dotted line) components at the 435 m level, as well as the neutron component data at the 3,000 m level (solid line); **b** variations in the geomagnetic cutoff rigidity $\Delta R_c(t)$ (dashed line) and the D_{st} -variation (solid line); **c** the change of the parameter γ of the primary variation spectrum, approximated by the power function $\Delta D(R) / D_o(R) = aR^{-\gamma}$; **d** the variation in the primary spectrum of the particles with rigidity 4 GV; **e** and **f** – the neutron component variations of magnetospheric and interplanetary origin at 435 m level (From Dorman et al., 1977)



Fig. 6.85 The data on the $\Delta N(R_{co}, t) / N_o$ of the NM component variations at March 25–27, 1976 from the worldwide network of stations (From Dorman et al., 1977)

Analysis of the data shows that the intensity increase can be clearly traced at the low-latitude stations and is almost invisible at the polar stations. This feature is characteristic of the effect of the geomagnetic cutoff rigidity variation. Hence, the decrease in the geomagnetic cutoff rigidity detected with the spectrograph in Irkutsk (panel b in Fig. 6.84) during the main phase of the magnetic storm is real.

6.20.3 Variations of ΔR_c on Different CR Stations and Dependence of ΔR_c on R_{co}

It is of interest to estimate ΔR_c for each CR station and to study the dependence on R_{co} . To isolate the magnetospheric part from the observed $\Delta N(R_{co},t)/N_o$ for each station, the data of the primary spectrum variations obtained with the spectrographic

26

March 1976

27





method (panels c and d in Fig. 6.84) were used. Panel f in Fig. 6.84 shows the behavior of the primary CR spectrum $\Delta D(R,t) / D_o(R)$ for the particles with a rigidity of 4 GV for the approximation of the spectral variations by a function of the form $\Delta D(R) / D_o(R) = aR^{-\gamma}$. The resultant variations of the geomagnetic cutoff threshold for the worldwide network of stations are presented in Fig. 6.86.

0.2

0

()0 2⁰ −0.2 2¹ −0.4

-0.6

-0.8

-1.0

-0.8

-0.6

-0.2

0

2

6

 $R_{co}(GV)$

4

8

10

12

(c) -0.4 25

The data displayed in Fig. 6.86 have been used to plot the dependence of ΔR_c from R_{co} by averaging over the interval 09.00–20.00 UT on March 26 (see Fig. 6.87). The peak of the curve $\Delta R_c = f(R_{co})$ at $R_{co} \approx 3-5$ GV and the descending branches are indicative of the geomagnetic latitude limitless of the size of the westward drift current in the magnetosphere responsible for the main phase of the magnetic storm.

6.20.4 Estimation of Ring Current's Properties

Assuming, as some approximation, that the real current is the ring current, the total intensity and the effective radius of the ring current may be estimated using the data on $\Delta R_c = f(R_{co})$ and $D_{st}(t)$ in the frame of theoretical model calculations described

in Section 6.6–6.7. The comparison has shown that the magnetic moment of the ring current relative to the earth's magnetic moment is $M_{\rm rc}/M_{\rm E} \approx 0.34$ and the relative radius $r_{\rm rc}/r_{\rm E} \approx 4.5$. Naturally, the actual structure of the current is more complex. It seems, therefore, that the real system of the drift current exhibits a spatial structure intermediate between the threadlike ring and the distributed current, over a sphere with the intensity proportional to the cosine of latitude.

Thus, the analysis of the data from the Sayan spectrographic complex for the magnetic storm of March 26, 1977 has shown that, apart from a Forbush decrease, the geomagnetic cutoff rigidity decrease also occurred due to the enhancement of the westward drift ring current.

6.21 Estimates of the Parameters of the Magnetospheric Ring Current During Magnetic Storms on the Basis of CR Data

6.21.1 The Matter of Problem and Observational Data

The spectrographic method permits the information on the variations of interplanetary and atmospheric as well as geomagnetic origin, to be derived from groundbased CR observation data. The geomagnetic effects in CRs are mainly due to the earth's magnetic field variations and, therefore, their study is of interest when examining the sources of the geomagnetic disturbances. According to Akasofu and Chapman (1972), the magnetospheric ring current is the main source of geomagnetic disturbances during magnetic storms. Determination of the ring current radius on the basis of ground-based magnetic data cannot be unambiguous and involves some errors (Isaev and Pudovkin, 1972). It is of great interest, therefore, to gain additional information on the generated current system (Dorman et al., 1979). The trajectories of the primary CR particles are markedly affected by the earth's magnetic field at distances smaller than several radii of the earth. Therefore, although the ring current results in an increase of the earth's magnetic moment at heliocentric distances outside the ring current, such an increase cannot practically affect the CR. The CR trajectories are significantly affected by the ring current in the region of and inside the ring current, thereby decreasing the threshold geomagnetic cutoff rigidity $\Delta R_{\rm c}$. The data displayed in panels a in Figs. 6.88–6.90 for magnetic storms of June 17-22, 1972, August 4-11, 1972, and March 26-28, 1976 confirm this conclusion.

6.21.2 Analysis of Data in the Frame of Two Used Models of Ring Current

The solid curves in panel a of Figs. 6.88–6.90 show the behavior of ΔR_c and the dashed curves present the D_{st} - variations in the same period. The analytical solution



Fig. 6.88 Event in June 1972. See the explanation in text (From Dorman et al., 1979)



Fig. 6.89 Event in August 1972. See the explanation in text (From Dorman et al., 1979)

Fig. 6.90 Event in March 1976. See the explanation in text (From Dorman et al., 1979)



for the problem of finding the cutoff rigidities in the earth's dipolar field in the presence of the equatorial ring current has been given in Sections 6.6–6.7. The cutoff rigidities were calculated in terms of two models of current systems, namely the threadlike ring current and the current distributed over a sphere whose intensity is proportional to the latitude cosine. The following equations were obtained as a result of the calculations:

$$\Delta R_{\rm c} = (M_{\rm rc} / M_{\rm E}) \exp(2.83 - 1.72 \ln(r_{\rm rc} / r_{\rm E})) + 0.13 (r_{\rm rc} / r_{\rm E}) - 0.39 [\rm GV],$$
(6.135)

$$\Delta H = (M_{\rm rc} / M_{\rm E}) \exp(10.89 - 2.91 \ln(r_{\rm rc} / r_{\rm E})) [\rm nT]$$
(6.136)

for the ring current model where the current intensity is proportional to the latitude cosine, and

$$\Delta R_{\rm c} = (M_{\rm rc} / M_{\rm E}) \times (1.06 (r_{\rm rc} / r_{\rm E}) - 0.55) \,[{\rm GV}], \qquad (6.137)$$

$$\Delta H = (M_{\rm rc} / M_{\rm E}) \exp(11.37 - 3.30 \ln(r_{\rm rc} / r_{\rm E})) [\rm nT], \qquad (6.138)$$

for the model of the threadlike ring current. Here ΔR_c is the variation of the geomagnetic cutoff rigidity (in GV); ΔH is the magnetic field decrease on the earth's surface at the equator (in nT); r_{rc} is the ring current radius and M_{rc} is the magnetic moment

of the ring current. The two sets of Eqs. 6.135–6.136 and Eqs. 6.137–6.138 have been obtained for the point of CR observations with geomagnetic cutoff rigidity $R_c = 4 \text{ GV}$.

The analysis of the magnetic storms of June 17–22, 1972, August 4–11, 1972, and March 26–28, 1976 is presented here. One of the characteristic features of a geomagnetic storm on the earth's surface is a decrease of the horizontal component of the field at low and medium latitudes with subsequent recovery within several days. The data on the $D_{\rm st}$ -variation in the earth's magnetic field, and the values of $\Delta R_{\rm c}$ obtained from the Sayan spectrograph have been used on the basis of the sets of Eqs. 6.135–6.136 and Eqs. 6.137–6.138 to estimate $r_{\rm rc}/r_{\rm E}$, $M_{\rm rc}/M_{\rm E}$, and $I_{\rm rc}$ of the generated current systems during the above-mentioned magnetic storms. The current intensities $I_{\rm rc}$ (in Amperes), the radius $r_{\rm rc}/r_{\rm E}$ (in relative units of the earth's magnetic moment $M_{\rm E}$) obtained in terms of the above-mentioned models, are shown in panels b, c, and d of Figs. 6.88–6.90. The solid and dashed curves in the figures show the values of $I_{\rm rc}$, $r_{\rm rc}/r_{\rm E}$ and $M_{\rm rc}/M_{\rm E}$ obtained respectively in terms of the models of threadlike ring current and the current distributed proportionally to the latitude cosine.

6.21.3 Main Results and Discussion

It can be seen from the plots shown in Fig. 6.88 that the decrease in the horizontal component of the earth's magnetic field reached -170 nT at the beginning of June 17, while the ring current radius $r_{\rm rc}/r_{\rm E}$ decreased down to the value 4 and the current intensity increased up to $\sim 10^7$ Amperes. As the magnetic storm subsided, the current in the generated current system decreased and the radius (in terms of the spherical model) increased abruptly and remained constant for some period, whereas in terms of the threadlike current model, the radius increased gradually and remained approximately constant throughout the examined period. As regards the magnetic moment, the threadlike current model gives a value of $M_{\rm rc}/M_{\rm E}$ not bigger than 0.3, even during the main phase of magnetic storm, whereas the model of the current distributed over a sphere give a magnetic moment of the ring current exceeding the earth's magnetic moment (the highest values of $M_{\rm rc}/M_{\rm E}$ are not shown in panel d in Figs. 6.88 and 6.89 because of inconvenience of the scale). Similar conclusions may be drawn from examination of the magnetic storm of March 26–28, 1976.

At least five consecutive decreases in the earth's magnetic field occurred during the magnetic storm of August 4–11, 1972. At that time, a rather peculiar ring current belt was formed, which was characterized (Kovalevsky et al., 1978) by various types of consecutive injections during magnetospheric disturbances. At the same time, the behavior of the ring current radius was significantly different as compared with the cases discussed above, which is probably indicative of the validity of the assumption (Sizova, 1976; Sizova et al., 1977) of successive generation and superposition of the ring current layers (DR₁, DR₂, DR₃, etc.) which may coincide or differ in location. In other words, it may be considered that an individual ring current belt is formed during each magnetic storm. The examined period was also characterized by a constant geomagnetic cutoff rigidity during the ~ 100 nT magnetic field depression in August, 1972 event. It can be seen from panel c in Fig. 6.89, that during that period the ring current belt was formed at a distance of $\sim 2r_{\rm E}$.

Comparison between the results obtained in the two models of presentation of ring current has shown the following. The changes of the radius and, particularly, magnetic moment of the current system indicate that the model of ring current with intensity proportional to the latitude cosine is probably less real than the threadlike ring model. It may be assumed, therefore, that the lateral dimension (Z) is much less than the radius $r_{\rm rc}$ of the generated current system. Besides that, it is quite obvious that the estimates of the current and the radius obtained here for the current systems generated during magnetospheric disturbances have the meaning of some mean effective values. Thus, the analysis of the data on the $D_{\rm st}$ -variations of the earth's magnetic field and on $\Delta R_{\rm c}$ are indicative of formation of ring current belts within (3–6) $r_{\rm E}$. The ring current radius reduces during the main phase of magnetic storm. The parameters of the real model of the magnetospheric ring current should probably be intermediate between the models of threadlike ring current and current distributed over a sphere in proportion to the latitude cosine.

6.22 Interrelation Between Variations of the CR Cutoff Rigidity and the Geomagnetic *D*_{st}-Variation During Magnetic Storms

6.22.1 The Matter of Problem

It is well known that the CR Forbush effects are accompanied by magnetic storms. The D_{st} -variation used as a measure of the magnetospheric disturbances is mainly contributed to by the ring DR current located at (3–6) r_E . A much smaller contribution is from the DRT currents generated at greater distances (7–10) r_E and from the DCF current at the magnetospheric boundary (Akasofu and Chapman, 1974).

The magnetic disturbances can be seen in the CR detected on the earth as changes of the charged-particle motion trajectories, and hence the changes of the geomagnetic cutoff threshold rigidity R_c . It is of interest to find out the degree of the influence of the DR, DRT, and DCF currents on the variations of the R_c during magnetic storms.

6.22.2 Observational Data and Variations of R_c During Three Events

The relevant experimental data were obtained from the Sayan CR spectrograph near Irkutsk ($R_{co} = 3.81 \,\text{GV}$). The description of the instruments and the experimental techniques are given in Dvornikov et al., 1979(see also in Chapter 4 of Dorman, M2004). Figures 6.91–6.93 show three events of Forbush effects in CR inferred from the observations of the neutron component at sea level near Irkutsk (curves a in all three figures).

The behavior of the D_{st} -variation may be used as an indication of the disturbance degree of the earth's magnetic field and the power of magnetic storms (dashed curves c). Figures 6.91–6.93 also show the time variations of the geomagnetic cutoff threshold rigidity R_c (curves b) at Irkutsk where $R_{co} = 3.81$ GV for non-disturbed earth's magnetic field. Let the behavior of D_{st} and R_c in each of the events be intercompared.

In the first event (February 15–17, 1978, see Fig. 6.91), a moderate magnetic storm with a \sim 90nT depression in the main phase was observed. The behavior of R_c shows a clear increase by, on the average, 0.25 GV at a \pm 0.15 GV error in each individual 2-h value.

The second event (March 25–29, 1976, see Fig. 6.92) illustrates the unambiguous correspondence between the decreases of D_{st} and R_c . The field depression in the main phase of the magnetic storm reached -200 nT, while R_c decreased from $R_{co} = 3.81 \text{ GV}$ to 1.51 GV.



Fig. 6.91 The behavior of the geomagnetic D_{st} -variation (curve c) and the cutoff threshold rigidity R_c (curve b) during the Forbush effect of February 14–17, 1978 (curve a) detected with the Irkutsk neutron super-monitor at sea level ($R_{co} = 3.81 \text{ GV}$) (From Dorman et al., 1981)



Fig. 6.93 The observation period of July 5–14, 1979. The designations are the same as in Fig. 6.91 (From Dorman et al., 1981)

In the third event (July 5–14, 1979), no disturbances of the earth's magnetic field were inferred from the D_{st} data, whereas R_c decreased from $R_{co} = 3.81 \text{ GV}$ to 2.81 GV on July 9–10.

6.22.3 Discussion and Main Results

We shall try to explain the disagreement between the changes in D_{st} and R_c using the estimates obtained in Dorman et al. (1979) for the parameters of the magnetospheric current systems responsible for the earth's magnetic field depression and for the variations in R_c during the magnetic storms of June 17, 1972, August 4–5, 1972, and March 26, 1976 (see Section 6.21). The estimates of the relative radii of ring





current $r_{\rm rc} / r_{\rm E}$ and relative magnetic moments $M_{\rm rc} / M_{\rm E}$ were obtained in the frame of the simple model of the threadlike ring current. The smoothened curve in Fig. 6.94 shows the variations in $r_{\rm rc} / r_{\rm E}$ (calculated from the $\Delta R_{\rm c}$ data) as functions of the observed $D_{\rm st}$ values.

Figure 6.94 also presents the averaged curves b and c obtained in Kuznetsov (1979) and Lyons and Williams (1976) correspondingly from the direct satellite measurements in the magnetosphere. Curve a has been obtained by Zaytseva et al. (1971) from the data on the luminosity of the high-latitude auroral red arcs.

Curves a, b, c, and d in Fig. 6.94 exhibit the same trend of a decrease in the ring current size $r_{\rm rc}/r_{\rm E}$ with increasing depression of $D_{\rm st}$. Curve d obtained from the CR data runs above curves a, b, c obtained by other methods. This fact indicates that not only DR but also the more remote DRT currents affect CR. The increase in $R_{\rm c}$ on February 15–17, 1978 (see Fig. 6.91) is accounted for by the dominant (as compared with the DR currents) effect in CR of the compression of the magnetosphere by the enhanced DCF currents at the magnetospheric boundary. The above-mentioned features in the behavior of $R_{\rm c}$ may be used together with other methods to diagnose the state of the magnetosphere.

6.23 The CR Decreases at High Latitudes and Increases at Middle Latitudes During Magnetic Storms

6.23.1 The Cases When During Magnetic Storms at High Latitudes Observed CR Decreases but at Middle Latitudes CR Increases

The events of the CR intensity increase during the geomagnetic storm were examined in a number of papers (e.g., Wolfson and Nobles, 1970; Dorman, 1981; Dorman et al., 1981; Flückiger et al., 1987; Kudo et al., 1987a). Antonova et al. (1991) studied events where there was sufficient increase of CR intensity at the high-altitude and middle-latitude station Tyan Shan (3,340 m above sea level, cutoff rigidity 6.9 GV) during magnetic storms. For a detailed analysis eight events of magnetic storms were chosen where a small decrease was observed in the CR intensity at high-latitude stations and sufficient increase at the middle-latitude station Tyan Shan. The observed increases connected with the decreases of the cutoff rigidity during a magnetic storm. The values of cutoff rigidity, the amplitudes and exponent of the Forbush-decrease spectrum were calculated from the CR data and the radius of the ring current was estimated.

6.23.2 Main Equations for the Extended Spectrographic Method

The parameters of Forbush decrease and the change of cutoff rigidity R_c at Tyan Shan CR station were determined using the extended spectrographic method described in Dorman et al. (1981). Using this method we take into account that for high-latitude stations $W_i(R_c, R_c) = 0$, so at these stations effects of changing R_c (CR geomagnetic variations) will be negligible. According to this method, the CR intensity variation $\Delta N_i / N_{io}$ at *i*-station during the geomagnetic storm can be expressed by the following equation:

$$\frac{\Delta N_i}{N_{io}} = -\Delta R_{ci} W_i(R_{ci}, R_{ci}) + \int_{R_{ci}}^{\infty} \frac{\Delta D(R)}{D_o(R)} W_i(R_{ci}, R) \,\mathrm{d}R, \qquad (6.139)$$

where $\Delta D(R) / D_o(R)$ is the primary CR variation, $W_i(R_{ci}, R)$ are the coupling function for the neutron component, and ΔR_{ci} is the change of cutoff rigidity R_{ci} . Suggesting that i = 1, 2, 3, for stations Apatity (sea level), Tyan Shan (3,340 m), and Alma-Ata (806 m), accordingly, and that $W_i(R_{ci}, R_{ci}) = 0$ for Apatity, we have for

$$\Delta D(R) / D_o(R) = bR^{-\gamma} \tag{6.140}$$

the following three equations:

$$\Delta N_1 / N_{1o} = b \int_{R_{c1}}^{\infty} R^{-\gamma} W_1 \left(R_{c1}, R \right) \mathrm{d}R, \tag{6.141}$$

$$\Delta N_2 / N_{2o} = -\Delta R_c W_2(R_c, R_c) + b \int_{R_c}^{\infty} R^{-\gamma} W_2(R_c, R) \, \mathrm{d}R, \qquad (6.142)$$

$$\Delta N_3 / N_{3o} = -\Delta R_c W_3 (R_c, R_c) + b \int_{R_c}^{\infty} R^{-\gamma} W_3 (R_c, R) \, \mathrm{d}R, \qquad (6.143)$$

Taking into account the relation between $W_i(R_c, R)$ and polar coupling coefficient $W_{io}(0, R)$ (Dorman, M1974; see also Chapter 3 in Dorman, M2004) we obtain from the set Eqs. 6.141–6.143 the equation for determining the parameter γ :

$$\frac{0.14\Delta N_2 / N_{2o} - 0.20\Delta N_3 / N_{3o}}{\Delta N_1 / N_{1o}} = F(\gamma), \qquad (6.144)$$

where

$$F(\gamma) = \frac{1.4\int_{6.9}^{\infty} R^{-\gamma} W_{2o}(0,R) \, \mathrm{d}R - 1.2\int_{6.9}^{\infty} R^{-\gamma} W_{3o}(0,R) \, \mathrm{d}R}{\int_{0}^{\infty} R^{-\gamma} W_{3o}(0,R) \, \mathrm{d}R}.$$
 (6.145)

The function $F(\gamma)$ was tabulated for $0 \le \gamma \le 1$. After determining γ from Eq. 6.144 the parameter *b* may be easy determined from Eq. 6.141, and then from Eq. 6.142 or Eq. 6.143 we determine ΔR_c . An example of one of the chosen events is shown in Fig. 6.95, where accumulated data of CR intensity at Tyan Shan (3340 m), Alma-Ata (806 m), and high-latitude station Apatity (s. l.), as well as data on variation of *H*-component of geomagnetic field in Alma-Ata are shown.

6.23.3 CR and Magnetic Parameters for Eight Selected Magnetic Storms

The experimental data $\Delta N_2 / N_{2o}$ for Tyan Shan station and ΔH at Alma-Ata geomagnetic station as well as results of determinations of *b*, γ and ΔR_c are given in Table 6.14.

The date indicated in Table 6.14 corresponds to the CR intensity maximum increase. The average relative accuracy of *b*, γ , and ΔR_c is about 20%. It should be noted that the mean value of $(\Delta N_2 / N_{2o}) / (100 \text{ nT})$ of ΔH is in agreement with the theoretical curve for mountain stations from Kudo et al. (1987a) at $R_c = 6.9 \text{ GV}$.

6.23.4 Estimation of the Current Ring Radius

If we know the ΔR_c and ΔH amplitude of a geomagnetic storm, we can evaluate the radius r_{cr} of the ring current. It can be made within the frame of some analytic models, suggesting that the main phase of the geomagnetic storm and the increase of CR intensity are due to the ring current. We obtained the expression for the change of R_c using the model of Glickman and Shabansky (1975) where the current intensity in the ring depends on latitude λ as $\cos^2 \lambda$:





$$\Delta R_{\rm c} = R_c \left[\frac{\Delta H}{2H} \left(\frac{r_{\rm cr}}{r_{\rm E}} \right)^3 \left(1 - \frac{3a^3}{4r_{\rm E}^2} \right) - \left(\frac{a^3}{r_{\rm E}^3} \right) \left(\frac{\Delta H}{8H} - \frac{3}{4} \right) \right],\tag{6.146}$$

where

$$a = \sqrt{\frac{|e|M_{\rm E}}{mcv} \left(1 - \frac{v^2}{c^2}\right)^{0.5}},\tag{6.147}$$

and $M_{\rm E}$ is the dipole magnetic momentum of the earth and $r_{\rm E}$ is the earth's radius. The calculated values of $r_{\rm cr}$ are shown in Fig. 6.96 depending on ΔH . The solid line in Fig. 6.96 presents the results of the determination of $r_{\rm cr} (\Delta H)$ by the

Date	$\Delta N_2 / N_{2o} (\%)$	ΔH (nT)	b(%)	γ	$\Delta R_c (\text{GV})$
10.01.1976	3.7	115	1.5	0.30	0.52
26.03.1976	5.3	225	3.6	0.35	0.80
11.12.1977	2.0	140	1.6	0.17	0.38
28.08.1978	3.6	224	2.8	0.25	0.62
01.04.1979	2.4	50	2.0	0.10	0.48
05.03.1981	2.3	190	3.7	0.15	0.56
06.05.1988	2.6	155	2.4	0.10	055
10.10.1988	1.5	231	2.9	0.10	0.47

Table 6.14 CR and magnetic parameters for eight selected magnetic storms in 1976–1988 (FromAntonova et al., 1991)

Table 6.15 List of NM for Fig. 6.105

Station name		Short name	Geographic		Cutoff rigi-dity
			Lat. (°)	Long. (°)	(GV)
1	Climax	clmx	39.37	253.82	3.26
2	Lomnicky Stit	Lmks	49.20	20.22	4.31
3	Zugspitze	Zgsp	47.42	10.98	4.75
4	Hermanus	Hrms	-34.42	19.22	5.26
5	Pic du Midi	Picd	42.93	0.25	5.81
6	Rome	Rome	41.90	12.52	6.54
7	Mt. Norikura	Mtnr	36.12	137.65	12.11
8	Chacaltaya	Chcl	-16.31	291.85	13.20



Fig. 6.96 Values of r_{cr} in dependence from ΔH (From Antonova et al., 1991)

Intercosmos-19 data (Kuznetsov, 1979) in the range $50nT \le \Delta H \le 170$ nT and the dotted line is its extrapolation to the larger values of ΔH . There is agreement between the curve and Antonova et al. (1991) results of $r_{\rm cr}$.

6.24 Using the Simplest Version of the Global Spectrographic Method (BDY-Method) for Discriminating CR Magnetospheric Variations

6.24.1 The Matter of Problem and the Simplest Version of the Global Spectrographic Method

CR variations arising from the variations of geomagnetic cutoff rigidity ΔR_c can be observed during magnetic storms. The magnetospheric CR variation amplitude is a function of geomagnetic latitude and local time of a given observation point. All the classes of the extraterrestrial CR variations cannot be studied accurately without including the magnetospheric effects. On the other hand, the CR variation proper may be used to specify the quiet and disturbed magnetospheric models and to find the parameters of magnetospheric current systems (Dorman, M1963a,b and M1974; Dorman et al., M1971; Flückiger et al., 1986). The CR variations were calculated in Dorman et al. (1980), making allowance simultaneously for the extraterrestrial and magnetospheric effects on the basis of spectrographical method. In Dvornikov et al. (1984), cutoff rigidity variations were obtained for six regions of the globe where the CR detectors with different coupling coefficients were combined to form spectrographical complexes of detectors.

Considered in Sections 6.18-6.23, the determination of CR geomagnetic variations caused by the changing of cutoff rigidity in the frame of spectrographic method is valid mostly for cases when the anisotropic effects are much smaller than isotropic effects. In the case when the anisotropic effects cannot be neglected, it is necessary to use the global spectrographic method described in detail in Chapter 3 in Dorman (M2004). The problem is that usually, for using the global spectrographic method, it was supposed that there are no geomagnetic variations or corresponding corrections that are made on these variations and they are excluded from observational data. To solve this problem, in IZMIRAN at the beginning of the 1980s, the socalled simplest version of the global-spectrographic method (or the BDY-method) was developed by A. Belov, L. Dorman, and V. Yanke (Belov et al., 1983). The main idea of the BDY-method is to use, for determining of the extraterrestrial CR variation parameters, only data of high-latitude CR detectors for which cutoff rigidities are smaller than atmospheric cutoff and therefore the magnetospheric CR variations are negligible. The found parameters of the extraterrestrial CR variation may then be used to find the magnetospheric CR variation for only CR detectors at the middle and low-latitudes. In such a way, the planetary distribution of the geomagnetic cutoff rigidity variations can be determined. It is important that in this case the $\Delta R_{\rm c}$ values at different points are estimated independently of each other, and their determination is irrelevant to the model concepts concerning the latitude and longitude distribution of the magnetic storm effects.

In the framework of BDY-method we consider the variation in the counting rate of some CR detector *i* at a point with rigidity R_{ci} located at level h_i as:

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$$\frac{\Delta N_i(R_{ci}, h_i)}{N_{io}} = -\Delta R_{ci} W_i(R_{ci}, h_i) + a_o \int_{R_{ci}}^{\infty} R^{-\gamma} W_i(R, h_i) \, \mathrm{d}R + C_{10}^i a_{10} + C_{11}^i a_{11} \cos\left(\varphi_i - \varphi\right),$$
(6.148)

where $W_i(R, h_i)$ are the detector coupling functions; a_o and γ are the amplitude and the power-law spectral index of the isotropic part of extraterrestrial CR variation; a_{10}, a_{11} , and φ are, respectively, the amplitude components and the phase of the first harmonic of CR anisotropy; φ_i is the effective asymptotic longitude of station at observation moment; and C_{10}^i and C_{11}^i are the acceptance coefficients of detector *i* for the respective components of CR anisotropy (Yasue et al., M1982).

Here we will consider several examples of applications of this simplest version of the global spectrographic method for discriminating CR magnetospheric variations from observed CR variations.

6.24.2 Magnetospheric Effects on CR During Forbush Decreases in August 1972

In Baisultanova et al. (1987), the data from 55 neutron monitors are used to solve a set of global spectrographic equations of the type of Eq. 6.148 to discriminate the isotropic, anisotropic, and magnetospheric CR variations during the Forbush decreases in August 1972. The first stage is to calculate the isotropic and anisotropic variations using the data from 24 high-latitude NM including four high-mountain NM (south pole, Sulphur Mt., Mt. Washington, and Calgary). As we mentioned above, these NM are almost not affected by magnetic variations. The second stage is to correct the middle- and low-latitude NM data for the founded extraterrestrial CR variations. The discrepancies between observed CR variations and extraterrestrial CR variations are assumed to arise from the geomagnetic effects. It means that the remaining fraction of the variation, δ_i , was assumed to be of magnetospheric origin. So, from Eq. 6.148 it follows that the variation of geomagnetic cutoff rigidity ΔR_c is

$$\Delta R_{\rm c} = -\delta_i / W_i \left(R_{\rm ci}, h_i \right). \tag{6.149}$$

Such an approach makes it possible to reject the model concepts concerning the dependence of ΔR_c on the latitude and longitude of observation point when finding the ΔR_c value. As a result, the dependences of ΔR_c on geomagnetic cutoff rigidity and an observation point longitude for event in August 1972 were obtained. Figure 6.97 shows the behavior of different values on August 4–10, 1972. During the August 5, 1972 magnetic storm, the D_{st} -value reached about -125 nT. It was one of the deepest Forbush decreases in the history of CR observations. The ΔR_c values were found for 31 stations with geomagnetic cutoff rigidities ranging from 1.9 to 15.9 GV. Figure 6.97 presents the variations ΔR_c averaged over the stations with cutoff rigidities 1.9–3.0 GV and 5.0–7.0 GV.



Fig. 6.97 The behavior of different values on August 4–10, 1972: **a** CR intensity variations $\Delta N / N_o$; **b** spectral index γ ; **c** and **d** the median values ΔR_{c1} and ΔR_{c2} of the cutoff rigidity variations for the stations with rigidities 1.9–3.0 GV and 5.0–7.0 GV, respectively; **e** D_{st} -index of geomagnetic field variations (From Baisultanova et al., 1987)

Figure 6.97 shows that at nearly all stations, the most significant R_c variations were observed at the 2nd hour of UT on August 5, 1972. During this time the $\Delta R_{\rm c}$ value was negative everywhere and varied from ~ 0.4 to ~ 2.8 GV at Ahmedabad and 1.23 GV at Huancayo. The second peak in the R_c variations occurred at the 22nd and 23rd hours of UT at $D_{\rm st} \approx -100$ nT. During that period, the $\Delta R_{\rm c}$ value was smaller and varied from 0.4 to 1.2 GV. At the 13th–15th hours of UT, local minima are observed in both $D_{\rm st}$ (20–50 nT) and $\Delta R_{\rm c}$. The best correlation between $D_{\rm st}$ and ΔR_c observed at the stations with $R_c < 4 \,\text{GV}$ because, probably, the parameters of the isotropic and anisotropic extraterrestrial CR variation inferred from the highlatitude NM data are in better correspondence with the CR variation behaviors at the station with low cutoff rigidities compared with the stations with high R_c values. The data from the group of stations with $R_c < 4$ GV can also be used to discriminate the longitudinal magnetospheric effect. At the 2nd hour of UT the highest (for the given group) ΔR_c value of $\approx 1.12 \,\text{GV}$ was observed at the Swarthmore station which appeared at that time in the dawn longitude sector. All the remaining stations with $R_{\rm c} < 4\,{\rm GV}$ appeared at that time on the earth's dark side and showed $\Delta R_{\rm c} < 0.8\,{\rm GV}$.
Fig. 6.98 Longitude distribution of relative variations in cutoff rigidity $\Delta R_{ci}/R_{ci}$: (panel **a**) on August 5, 1972; (panel **b**) – on August 9, 1972 (From Baisultanova et al., 1987)



Panel a of Fig. 6.98 presents the longitude dependence at the 1st–3rd hours of UT on August 5, 1972 of the value $\Delta R_{ci} / R_{ci}$.

On August 9, the Forbush-decrease depth was comparatively small (<2%), while the magnetic storm was extremely strong. At the 11th and 12th hours of UT on August 9 the D_{st} value reached -154 nT and the largest cutoff rigidity variations were observed. However, in contrast to August 5 and to other known cases of magnetospheric CR variations, the ΔR_c value at those hours of August 9 increased, rather than decreased. At most of the NM, the ΔR_c value varied within 0.5–1.0 GV. At all the remaining hours of August 5–9, including the onset of the August 9 magnetospheric storm, the ΔR_c value was <0. Panel b of Fig. 6.98 shows the dependence of $\Delta R_{ci} / R_{ci}$ on local time. The variations on the earth's sunlit side are more substantial compared with its dark side. It is not excluded in this case that we deal with the currents on the magnetopause which were discussed earlier by Dorman et al. (1980) in connection with another case of cutoff rigidity rise during a magnetic storm.

Baisultanova et al. (1987) came to the conclusion that the cutoff rigidity variations inferred from CR data are relevant to, but not determined by, the D_{st} variations and can essentially supplement the information about magnetic storm development derived from magnetic measurements.

6.24.3 The Longitude and Latitude Dependences of the Geomagnetic Cutoff Rigidity Variations During Strong Magnetic Storms in May 25–26, 1967, December 17–18, 1971, and in August 4–5, 1972

In Antonova et al. (1990) the BDY-method (Belov et al., 1983; see also Section 6.24.1) was used to process the data on the Forbush decreases accompanied by magnetic storms using the data from the worldwide network of CR stations. During the first stage of the processing, the data from only the high-latitude stations were used to find the spectrum of the CR isotropic component and the components of the spherical harmonic of the anisotropy. During the next stage, the data from medium-and low-latitude stations, for which the reception factors are known, were corrected for extraterrestrial variations; the residue was regarded as being due to the magnetospheric effect. In this way, in Antonova et al. (1990) CR data obtained during strong magnetic storms in May 25–26, 1967, December 17–18, 1971, and August 4–5, 1972 were analyzed.

The anomalously intensive magnetic storm of May 25–26, 1967 was selected to make analysis of the planetary distribution of the variations of the threshold geomagnetic cutoff rigidities during the CR minimum at the main phase of the storm.

The given storm was very intensive, with a field depression in the its main phase $D_{st} = -(414-418)$ nT, and proved to be simple with regard to its structure and not complicated by any additional pulses. Obviously, the large-amplitude effects in D_{st} which are not complicated by second-order effects must be expected in the magnetospheric variations of CR during the given period. The R_c variations were obtained for 20 medium- and low-latitude CR stations. Figure 6.99 shows the $\Delta R_c (R_c)$ distribution in the minimum of the main phase at 04:00–05:00 UT on May 26.

Each dot in Fig. 6.99 is the mean of the R_c variations at an individual station over the 04.00–05.00 UT interval. It is seen that ΔR_c in the 2GV $\leq R_c \leq$ 4GV range decreases from $\Delta R_c \approx 0.1$ GV to $\Delta R_c \approx -1.2$ GV. At $R_c >$ 4GV, the ΔR_c changes little and exhibits a plateau up to $R_c \approx 14$ GV. It is seen that the cutoff rigidity distribution $\Delta R_c (R_c)$ during the very substantial field depression in the main phase minimum differs from the conventional distribution with the R_c variation maximum



Fig. 6.99 The $\Delta R_c(R_c)$ distribution in the minimum of the main phase at 04.00–05.00 UT on May 26 (From Antonova et al., 1990)



Fig. 6.100 The longitudinal distribution of the ΔR_c variations at 2–5 UT (panel **a**) and at 22 UT (panel **b**) of May 26, 1967 (From Antonova et al., 1990)

at 4–5 GV. Figure 6.99 does not show the ΔR_c values at two low-latitude stations (Mt. Norikura with $\Delta R_c \approx -2.2$ GV and Kula with $\Delta R_c \approx 1.8$ GV). The anomalous variations at these two stations become understandable when analyzing the longitudinal distribution of the ΔR_c variations (see panel a in Fig. 6.100).

Panel a of Fig. 6.100 shows that the ΔR_c variation maximum is observed in daylight hours, whereas at dawn and night hours the ΔR_c values are lower, although they still remain high. The Mt. Norikura station was then on the dayside (11.00– 14.00 LT), and Kula in the dusk sector (16:00–19:00 LT). However, the longitudinal ΔR_c asymmetry does not exhibit its largest amplitude during the main phase minimum.

Panel b of Fig. 6.100 presents the longitudinal distribution in the beginning of the development of the main phase of the magnetic storm at 22:00 UT on May 26, 1967 ($D_{st} = -140$ nT). The largest amplitude of ΔR_c is observed at Kula (12-h LT meridian) and at Huancayo and Chacaltaya (the dusk sector).

The magnetic storm of December 17–18, 1971 was selected because of a peculiar character of the latitude distribution of the geomagnetic cutoff rigidity variations during its initial phase (Flückiger et al., 1987). The ΔR_c variations were obtained for 25 middle- and low-latitude stations (Baisultanova, 1988). To exclude a possible superposition of the effects, the geomagnetic cutoff rigidity variations ΔR_c were studied for the CR stations with $R_c > 4.5 \text{ GV}$ to find their longitude asymmetry. Figure 6.101 shows the development of the longitude asymmetry of ΔR_c during the initial phase of the magnetic storm at the consecutive moments of 16:00, 17:00, and 18:00 UT on December 17, 1971.

The day–night asymmetry with particularly high values of ΔR_c is seen in the dusk sector at 16:00 and 17:00 UT (at Potchefstroom and Rome). The minimum variations were observed near the noon meridian (at Mexico, Huancayo, and Chacaltaya). At 18:00 UT the effect decreased ($\Delta R_c \approx \pm 0.2 \text{ GV}$).

Antonova et al., 1990)



Figure 6.102 presents the $\Delta R_c(R_c)$ distribution at consecutive moments of 16:00, 17:00, and 18:00 UT on December 17, 1971 taking into account the longitudinal effect.

From Fig. 6.102 it is seen that the cutoff rigidity rises during the initial phase of the storm. Especially strong variations are observed in the $R_c = 2.0 - 3.5 \,\text{GV}$ range (Leeds, Kiel, Moscow, Utrecht, Dourbes, and Kiev). At each following hour the ΔR_c variations decreased. The ΔR_c variations in the given rigidity range were still high (0.2–0.4 GV) at 18.00 UT, although $\Delta R_c \approx \pm 0.2$ GV had been already observed throughout the globe. Such a situation arises due to the compensating effect of the ring DR currents developing in the magnetosphere which affect the cutoff rigidity least of all in high latitudes and most of all in the 4-5 GV range, whereupon the ring current effect decreases gradually at higher rigidities. The given $\Delta R_{\rm c}(R_{\rm c})$ distribution agrees quantitatively with the result obtained by Flückiger et al. (1987). The quantitative difference (a systematic difference of about $0.2 \,\text{GV}$) may be due to (1) different methods used to exclude the isotropic component from the observed variations, and (2) a minor difference in the reference values of the cutoff rigidities.

Fig. 6.102 The $\Delta R_c (R_c)$ distribution at 16:00, 17:00, and 18:00 UT on December 17, 1971 (From Antonova et al., 1990)



The planetary distribution of ΔR_c in the initial stage of magnetic storm was studied for August 4–5, 1972. The disturbance was produced by the interaction of the earth's magnetosphere with a very dense stream of high conductivity solar wind plasma whose velocity reached about 2,000 km/s at that time. The most substantial R_c variations were observed at all CR stations at 1:00–2:00 UT on August 5, with the ΔR_c value being positive during that interval. The increase of the threshold rigidities of geomagnetic cutoff was due to the earth's magnetosphere compression by the high-velocity solar wind stream under the northward orientation of the IMF B_z component (which corresponds to the initial magnetic storm stage).

Figure 6.103 shows the longitudinal distribution of ΔR_c at 1:00 UT and 2:00 UT on August 5, 1972.

A longitudinal asymmetry of ΔR_c in Fig. 6.103 with a maximum on the dayside ($\Delta R_c \approx 1.8 \,\text{GV}$ at Brisbane) was observed at 1:00 UT. At 2:00 UT, the dawn–dusk asymmetry of the ΔR_c distribution set with the maximum $\Delta R_c \approx 1.9 \,\text{GV}$ (Mexico) in the dusk sector and the minimum $\Delta R_c \approx 0.6 \,\text{GV}$ (Pic du Midi and Tbilisi) on the dawnside.

Figure 6.104 presents the $\Delta R_c(R_c)$ dependence. It is seen that the cutoff rigidity increases markedly throughout the globe during the initial phase of the storm because of the effect of the magnetopause DCF-currents. The anomaly in the rigidity range $R_c \sim 4$ GV arises from the compensating effect of the ring DR currents.

Fig. 6.103 The longitudinal distribution of ΔR_c at 1:00 UT and 2:00 UT on August 5, 1972 (From Antonova et al., 1990)



Fig. 6.104 The $\Delta R_c(R_c)$ dependence at 1:00 UT and 2:00 UT at August 5, 1972 (From Antonova et al., 1990)

The conclusion of Flückiger et al. (1987), that the rigidity dependence of the $\Delta R_c(R_c)$ increase during the initial phase differs substantially from the rigidity dependence during the main and recovery phases of the magnetic storm, may be

repeated in the given case too. Besides, definite conclusions can be drawn concerning the dynamics of the rigidity and longitude ΔR_c distributions during the initial phase of the magnetic storm, namely (i) the variations of the geomagnetic cutoff rigidity and the longitudinal asymmetry decreased, as the magnetic storm developed, more rapidly at $R_c \approx 4.5 \,\text{GV}$ than at $R_c \approx 3.5 \,\text{GV}$ because of the compensating effect of the DR currents which was minimum at $R_c \leq 3 \,\text{GV}$ and maximum at $R_c \approx (4-5) \,\text{GV}$ and decreased at higher cutoff rigidities; and (ii) the recovery of geomagnetic cutoff rigidity is more inertial in the range $2 \,\text{GV} \leq R_c \leq 3.5 \,\text{GV}$. In this case the R_c variations are due mainly to the processes occurring on the magnetopause, in particular to the DCF currents at the magnetospheric boundary. Besides, it is seen that the magnetospheric effect in CR due to the magnetopause DCF currents, may appear to be comparable with, or even to exceed, the effect due to magnetospheric ring currents.

The above analysis shows that (1) during very intensive magnetic storms, in the CR minima of their main phases, the R_c variations at low latitudes may be at least the same as the R_c variations at medium latitudes; (2) during the main phase of the very intensive magnetic storm, a longitudinal asymmetry of the planetary distribution of the geomagnetic cutoff rigidity variations is possible, with the maximum variations on the dayside and with conservation of substantial R_c variations in the dusk sector; and (3) the most significant longitudinal asymmetry of the planetary ΔR_c distribution with the maximum variations at the noon meridian was observed at the beginning of the development of the main phase of the storm. Obviously, the asymmetry at the beginning of the formation stage of the ring DR current is larger than the asymmetry observed during its stabilization period.

Antonova et al. (1990) came to the conclusion that the longitudinal and cutoff rigidity distributions of ΔR_c during different stages of a magnetic storm are a superposition of the dynamic processes occurring in the magnetosphere and in the magnetopause. During some short periods, when large amplitudes of the ΔR_c variations are observed, their planetary distribution may prove to be of a very complicated form, in discordance with the commonly accepted concepts. This circumstance must be allowed for when studying the CR variations during magnetic storms.

6.24.4 Changes of CR Cutoff Rigidities During Great Magnetic Storms in May 1967, August 1972, and November 1991

CR variations associated with changes of the cutoff rigidity during large magnetic storms were investigated in Yoshida and Wada (1959), Kondo et al. (1960), and Obayashi (1961). The appearance and development of the magnetopause and ring currents change the cutoff rigidities of CRs. The dependence of these changes on the latitude and longitude of NM arising from the azimuthal asymmetry of the ring current system was studied in Dorman and Shatashvili (1961, 1962, 1964), and Yoshida et al. (1968). The cutoff rigidities are reduced most significantly during the asymmetric phase of the magnetic storm (Kudo et al., 1987b). During the initial phase of

a magnetic storm associated with the magnetopause currents, there is an increase in cutoff rigidities (Flückiger et al., 1987).

In Baisultanova et al. (1995), magnetospheric variations of CR were discriminated from the data of middle- and low-latitude NM by the BDY-method (see Section 6.24.1). The changes of the cutoff rigidity were found for great magnetic storm events in May 1967, August 1972, and November 1991. Isotropic, anisotropic, and magnetospheric parameters of CR variations during large geomagnetic storms were obtained by means of the BDY-method. This method is based on the following procedure. The data of high-latitude neutron monitors were used to calculate the isotropic and anisotropic parameters of the extraterrestrial CR variations. We take into account that CR variations associated with the main phase of geomagnetic storms at the high-latitude neutron monitors are negligible. CR variations observed by detector *i* with cutoff rigidity R_c and coupling function $W_i(R_c, R, h_i)$ at level h_i are described by the equation:

$$\frac{\Delta N_i}{N_{io}} = A_o \int\limits_{R_c}^{\infty} R^{-\gamma} W_i(R_c, R, h_i) \,\mathrm{d}R + C_{xi}A_x + C_{yi}A_y + C_{zi}A_z, \tag{6.150}$$

where A_o is the variation of the isotropic part of the primary CR flux; γ is the index of power-law spectrum of primary CR variation; A_x , A_y , A_z are three components of the first harmonic of CR anisotropy; and C_{xi} , C_{yi} , C_{zi} are the associated coupling coefficients. The solution of the system of Eq. 6.150 gives the parameters A_o , γ , A_x , A_y , A_z . Then, using these parameters, the magnetospheric component of CR variations can be separated. The isotropic and anisotropic components are subtracted from the CR data observed at the middle- and low-latitude stations. The residuals are considered as the result of magnetospheric effect:

$$\delta_{\mathrm{mag},i} = \Delta N_i / N_{io} - \delta_{\mathrm{is},i} - \delta_{\mathrm{anis},i} = -\Delta R_{\mathrm{c}i} W_i \left(R_{\mathrm{c}i}, R_{\mathrm{c}i}, h_i \right), \qquad (6.151)$$

where $\delta_{is,i}$, $\delta_{anis,i}$ are the isotropic and anisotropic parts of the CR variation observed by the detector *i* with the coupling function $W_i(R_{ci}, R, h_i)$. Thus, the variation of cutoff rigidity is

$$\Delta R_{\rm ci} = -\delta_{\rm mag,i} / W_i (R_{\rm ci}, R_{\rm ci}, h_i). \tag{6.152}$$

The cutoff rigidity variations at different NM are determined independently of each other, and their determination is irrelevant to the model concepts concerning the latitude and longitude distribution of the magnetic storm effects.

Baisultanova et al. (1995) have chosen the period of May 1967 to present the results obtained by this method for the main phase of magnetic storm. During May 1967 the depression of $D_{st} = -387 \text{ nT}$ and -123 nT was observed at the minimum of the main phase of the large magnetic storm on May 25–30 and the storm on May 2–5, respectively. Figure 6.105 shows the time changes of CR cutoff rigidities calculated for different NM stations with $3 \text{ GV} < R_c < 14 \text{ GV}$.

The latitude dependence of the cutoff rigidities decreases during the main phase of the large magnetic storm is shown in Fig. 6.106. It is seen from a comparison



Fig. 6.105 The D_{st} -variations and the calculated variations of CR cutoff rigidity on different NM (see Table 6.15) in May, 1967 (From Baisultanova et al., 1995)



Fig. 6.106 The latitude dependence of CR cutoff rigidity variations at 06–07 UT on May 26, 1967 (From Baisultanova et al., 1995)

with the discussed events in Fig. 6.106, that the effect caused by the ring currents can be observed at the low-latitude stations with large R_c as well (Mt. Norikura, Chakaltaya).

The BDY-method was also applied to study the event on August 4–9, 1972. Because the Forbush decrease on August 4–9, 1972 has been investigated in



Fig. 6.107 The latitude dependence of the cutoff rigidity variations at 12–13 UT on August 4, 1972. The fitting curve is determined by Eq. 6.153 (From Baisultanova et al., 1995)

many papers (e.g., Belov et al., 1983; Dvornikov et al., 1987; Baisultanova et al., 1987), Baisultanova et al. (1995) treats only the effect of the magnetopause rings. Figure 6.107 shows the latitude dependence of the cutoff rigidity variations at 12–13 UT on August 4, 1972.

From Fig. 6.107 it can be seen that the maximum of the cutoff rigidity variations was observed at the high latitude. One can see from comparison of Figs. 6.106 and 6.107, that the rigidity dependence $\Delta R_c(R_{co})$ is rather different for the minimum of the main phase of the magnetic storm and the periods when the effect of the magnetopause currents is dominant. The behavior of $\Delta R_c(R_{co})$ agrees well with the results obtained in Flückiger et al. (1987). A large amplitude of the cutoff rigidity variations can be explained by the interaction of the magnetosphere and the high-speed stream. The magnetosphere was strongly depressed and the magnetopause was at the $4r_E$ distance from the earth (Zastenker et al., 1978). This dependence of $\Delta R_c(R_{co})$ seems to be typical for the effects caused by the magnetopause currents.

Figure 6.107 also shows the fitting curve described by the relation:

$$\Delta R_c(R_{co}) = 0.98 \exp(-0.6R_{co}) + b, \qquad (6.153)$$

where ΔR_c and R_{co} are in GV.

Baisultanova et al. (1995) came to the conclusion that the results obtained above correspond to the common views on the time-development and latitude dependence of the cutoff rigidity $\Delta R_c (R_{co})$ during the different phases of the magnetic storms.



Fig. 6.108 The D_{st} -variation and uncorrected and corrected for magnetospheric effect (thin and thick solid lines, correspondingly) variations of 10 GV CR density during the Forbush decrease in November, 1991 (From Baisultanova et al., 1995)

6.24.5 On the Correction of CR Data on Geomagnetic Variations

Investigations of CR geomagnetic variations are important not only for magnetosphere research but also in research of any type of extraterrestrial CR variation. Particularly, Baisultanova et al. (1995) showed that the magnetospheric variation of CRs should be taken into account in analyzing the NM data during Forbush decreases, because they are usually accompanied by the magnetic storm. The BDY-method allows us to correct the neutron monitors data for the magnetospheric effects. Figure 6.108 illustrates the influence of these corrections on the determination of the isotropic component of the Forbush decrease in November 1991.

From Fig. 6.108 one can see that the difference between the corrected and uncorrected results is more than 1%. In Baisultanova et al. (1995), it was also shown that the related error for spectral index is $|\Delta \gamma| \ge 0.1$.

6.25 Magnetospheric Currents and Variations of Cutoff Rigidities on October 20, 1989

6.25.1 The Matter of Problem

Changes in the CR cutoff rigidities for middle and low latitudes are evaluated in Struminsky and Manohar (2001) for the Forbush decrease in October 20–22, 1989 from hourly values of the D_{st} index and the modified $D_{st,rc}$ index, which accounts for only an increasing of the ring current and $D_{st,mp}$ index, which in turn accounts

only for magnetopause currents. The magneto-storm dynamical model using solarwind data available for the initial phase of the event obtains values of the modified $D_{\text{st.rc}}$ and $D_{\text{st.mp}}$ indexes. Struminsky and Manohar (2001) note that, in the practice of CR variation studies one needs to know changes in the cutoff rigidity. One way for determining cutoff rigidity changes is trajectory calculations of particle propagation in the earth's magnetic field (see Chapter 3 and review in Smart et al., 2000). However, the earth's magnetosphere is dynamic, but the most widely used magnetospheric models are quasi-static. Apparently, the problem is far from its final solution, especially for periods of large geomagnetic activity. Moreover, the trajectory calculations in the earth's magnetic field take a lot of time and it is difficult to apply them directly for a particular period of the geomagnetic activity to study a particular CR event. Simple models, which use some precalculated results, have been elaborated for this purpose. Struminsky and Manohar (2001) apply the procedure of Flückiger et al. (1986) to calculate changes of cutoff rigidities during the Forbush decrease on October 20-22, 1989. They developed this procedure and separated the $D_{\rm st}$ index into its contributions due to the ring and magnetopause currents for October 20–22, 1989 using the magneto-storm dynamical model of Olson and Pfitzer (1982). Input parameters of the model are solar-wind and geomagnetic-field data. All data were taken from the SPIDR database (http://spidr.ngdc.noaa.gov). Unfortunately the solar-wind data are not available for the later period of the event on October 21–22, 1989. The Forbush decrease on October 20–22, 1989 is one of the greatest and interesting events of the 22nd solar cycle. The decrease started on the background of the October 19 ground-level enhancement and close to arrival of protons with energy >500 MeV associated with the shock front. These protons were observed during several hours after the shock passage in the stratosphere in Moscow, but the Moscow neutron monitor did not show a clear effect at that time. The Forbush decrease lasted for about 3 days and during its recovery phase the large GLE on October 22, 1989 occurred. Estimates of cutoff rigidity changes are the first step in studying CR variations of different origin during this complex event.

6.25.2 Procedure of CR Cutoff Rigidity Calculations

Flückiger et al. (1986) proposed a procedure to estimate changes of vertical cutoff rigidity and asymptotic directions during geomagnetically active time periods for any specific low-latitude or mid-latitude location characterized by coordinates λ_m , φ_m . In this model, the change of the rigidity of first discontinuity R_1 is presented as a weighted sum of the horizontal component of the equatorial surface magnetic field:

$$\Delta R_1(\lambda_m, \varphi_m, t) \approx \sum_{n=0}^7 g_n(\lambda_m) \Delta H_{\text{eq}}(\varphi_m + n \times 15^\circ, t).$$
 (6.154)

The major changes of the cutoff rigidity are the result of magnetic perturbations within $\sim 60^{\circ}$ E of the observation location and magnetic perturbations located more

than $\sim 120^{\circ}$ E have practically no effect on the cutoff rigidity values. Therefore, values of the equatorial magnetic field are sampled in this model at intervals of 1 h local time from 00.00 to 07.00 to the east of the specified location. Its values at one particular moment $t = t_o$ at the point with local time t_L are assumed to be equal

$$\Delta H_{\rm eq}(t_{\rm L}, t = t_o) = D_{\rm st}(t = t_o) + 50 \times \sin(2\pi t_{\rm L}/24). \tag{6.155}$$

The corresponding weighting factors $g_n(\lambda_m)$ for effective cutoff rigidities within the interval 3 GV < R_c < 13.5 GV are found in Flückiger et al. (1986). Besides, Flückiger et al. (1986) show that the rigidity of first discontinuity, the upper cutoff rigidity, and the effective cutoff rigidity change similarly, so one can easily estimate changes of the cutoff rigidities for desired periods of the geomagnetic activity. The described procedure is valid in locations, where $R_c > 3$ GV and the accuracy of determining the change of effective cutoff rigidity is about ± 0.1 GV.

6.25.3 Applying to NM Data of Moscow, Kiev, and Rome

Struminsky and Manohar (2001) applied the described procedure to get changes in the effective cutoff rigidities during the Forbush decrease on October 20–22, 1989 by using NM data of stations Moscow ($R_c = 2.43 \text{ GV}$), Kiev (3.57 GV), and Rome (6.32 GV). They note that in the case of Moscow the weight factors $g_n(\lambda_m)$ in Eq. 6.155 have been approximated to the region $R_c < 3 \text{ GV}$, so errors in determining the effective cutoff rigidity change for Moscow might be higher than $\pm 0.1 \text{ GV}$. Figure 6.109 shows the results of Struminsky and Manohar (2001) calculations for these three NM.

6.25.4 Estimation of Magnetospheric Currents

The close connection between changes in R_c and the ring current allows us to estimate the relative strength of ring and magnetopause currents by knowing the changes in R_c and values of the D_{st} index (Flückiger et al., 1990). Struminsky and Manohar (2001), within the frame of this research, tried to solve the inverse problem: to determine the changes in R_c using the D_{st} index and model values of magnetospheric current's strength.

In general, the D_{st} index reflects variations of the ring current rather well; the effects of other current systems are negligible. However, in some particular cases, when the magnetosphere is strongly compressed, the opposite effects of the ring current and magnetopause current may be comparable. Therefore, in order to estimate changes in R_c , it would be better to remove the contribution of the magnetopause current from the D_{st} index. Following the paper by Olson and Pfitzer (1982) and using solar-wind and IMF data, it is possible to separate D_{st} into two parts:



Fig. 6.109 Variations of effective cutoff rigidities for vertical incident CR particles at stations Moscow, Kiev, and Rome during October 20–22, 1989 (From Struminsky and Manohar, 2001)

$$D_{\rm st}(t) = D_{\rm st,rc}(t) + D_{\rm st,mc}(t),$$
 (6.156)

where $D_{\text{st,rc}}(t)$ is due to the ring current, and $D_{\text{st,mc}}(t)$ – to the magnetopause current.

The magnetopause component of the D_{st} - index is

$$D_{\rm st,mc}(t) = 25 \times (S_{\rm m}(t) - 1), \qquad (6.157)$$

where

$$S_{\rm m}(t) = (10.5 / r_{\rm mc}(t))^3$$
 (6.158)

is the variation in the strength of the magnetopause current and $r_{\rm mc}(t)$ is the distance to the magnetopause in units of the earth's radius $r_{\rm E}$. The value of $r_{\rm mc}(t)$ is determined by the balance of the dynamic pressure of the solar wind and pressure of the earth's magnetic field:

$$r_{\rm mc}(t) = 98 \times \left(\rho_{\rm sw} u_{\rm sw}^2\right)^{-1/6},$$
 (6.159)

where ρ_{sw} and u_{sw} are the density and velocity of the solar wind.

The strength of the ring current relative to its quiet time strength is given by

$$S_{\rm rc}(t) = 1 - 0.025 D_{\rm st, rc}(t)$$
 (6.160)



Fig. 6.110 Increasing of the magnetopause current (mc), ring current (rc), and tail current (tc) relatively to their quite values (From Struminsky and Manohar, 2001)

The relative strength of the tail current is assumed to be proportional to the Pointing vector of the IMF multiplied by a factor of 0.15 and by the cross section of the magnetosphere, i.e.,

$$S_{\rm tc} = 2 \times 10^{-7} u_{\rm sw} (r_{\rm mc} B)^2$$
. (6.161)

Using Eqs. 6.159–6.161, it is possible to determine the increasing of the magnetospheric currents relative to their quite values of October 20, 1989 (see Fig. 6.110).

Substituting the relative strength of the magnetopause current into Eq. 6.157 we get $D_{\text{st,mc}}(t)$, and then by Eq. 6.156, $D_{\text{st,rc}}(t)$ can be determined. Figure 6.111 presents the results of these calculations.

From Fig. 6.111 one can see significant changes of magnetopause current between 15.00 and 20.00 UT. The effect of the magnetopause current is really large and compensates about one-third of the ring current effect.

6.25.5 Recalculations of Cutoff Rigidity Changes

Struminsky and Manohar (2001) repeated calculations of the cutoff rigidity changes described in Section 6.25.3 using the modified $D_{\text{st,rc}}(t)$ index from Section 6.25.4. Figure 6.112 shows the difference between vertical cutoff rigidities calculated using $D_{\text{st}}(t)$ and $D_{\text{st,rc}}(t)$ indexes for Moscow, Kiev, and Rome.



Fig. 6.111 Time variations of the $D_{st}(t)$ index and contributions to $D_{st}(t)$ due to the ring current $D_{st,rc}(t)$ and the magnetopause current $D_{st,mc}(t)$ (From Struminsky and Manohar, 2001)



Fig. 6.112 Differences between vertical cutoff rigidities calculated using $D_{st}(t)$ and $D_{st,rc}(t)$ indexes for Moscow, Kiev, and Rome (From Struminsky and Manohar, 2001)

From Fig. 6.112 it is clear that when a relative strength of the magnetopause current is large, this difference is much greater than the error of ± 0.1 GV estimated in Flückiger et al. (1986).

6.25.6 Checking Using Balloon and Satellite Measurements

The above-described results were compared with the cutoff rigidity changes estimated by using data of the balloon experiment over Moscow during October 20, 1989 (Struminsky, 1992). The shapes of the CR absorption curves in the stratosphere strongly depend on the spectrum of primary particles and their minimum rigidity. During three balloon flights between 13.00 and 19.00 UT on October 20, 1989, the obtained absorption curves revealed a presence of additional protons with rigidity $>1 \pm 0.25$ GV; therefore, the cutoff rigidity in Moscow dropped by about 1.5 GV. These protons apparently had the same origin as the second hump clearly seen in the GOES-7 proton data (Struminsky, 2001). Changes of the cutoff rigidities obtained with the modified $D_{\text{st,rc}}(t)$ index instead of the $D_{\text{st}}(t)$ index show better agreement with both experimental results of balloons and satellite.

6.25.7 Summary and Discussion

In Struminsky and Manohar (2001), the changes in the cutoff rigidities were evaluated from hourly values of the $D_{st}(t)$ index for different CR stations on October 20–22, 1989 using the procedure proposed by Flückiger et al. (1986). In order to take into account the effects of the ring current only, hourly values of the $D_{st}(t)$ index were modified according to the dynamical model of magneto-storm (Olson and Pfitzer, 1982) by removing the contribution of the magnetopause current. Solar protons of about atmospheric cutoff energy were measured over Moscow in the stratospheric balloon experiment on October 20, 1989. The changes in CR cutoff rigidities obtained for Moscow with the modified $D_{st,rc}(t)$ index show better agreement with these experimental results. Struminsky and Manohar (2001) showed that the checking by satellite data also supports the using of the modified $D_{st,rc}(t)$ index instead of the $D_{st}(t)$ index in the procedure for determining the change of CR cutoff rigidities developed by Flückiger et al. (1986).

Struminsky and Manohar (2001) note that in general the D_{st} index reflects variations of the ring current rather well; the effects of other current systems are negligible. However, in some particular cases, when the magnetosphere is strongly compressed, the opposite effects of the ring current and the magnetopause current may be comparable. Therefore, in order to estimate changes in R_c , it would be better to remove the contribution of the magnetopause current from the D_{st} index.

Chapter 7 Magnetospheric Models and their Checking by Cosmic Rays

7.1 The Earth's Magnetic Field with a Warped Tail Current Sheet (Tsyganenko-89 Model)

7.1.1 The Matter of Problem

Tsyganenko (1989) noted that the region near the inner edge of the plasma sheet in the nightside magnetosphere plays a key role in the dynamics of disturbances. The structure of the geomagnetic field and plasma in this region is extremely variable, since it is just here that the boundary between the "spheres of influence" of the earth's internal field sources and the magnetotail currents, controlled by the solar wind, is located. Several experimental facts concerning this region can be pointed out, which should be taken into account in any quantitative model aimed at an adequate representation of the average magnetic field and current distribution. There are the following results (Tsyganenko, 1989):

1. Strong evidence exists that an intense and thin current sheet can approach the earth as close as $(3-5)r_{\rm E}$ at the nightside. This was suggested by Sugiura (1972) as a direct implication of the observed features of the ΔB distribution in the inner magnetosphere. Hedgecock and Thomas (1975) pointed out that the tail-like configuration is clearly discernible in the HEOS magnetic field data at tailward distances of $(6-8)r_{\rm E}$, with the current sheet thickness less than $1r_{\rm E}$. Lin and Barfield (1984) showed in a statistical study that the tail-like fields can often be observed at geosynchronous orbit in the midnight sector, with increasing probability during disturbed periods, and estimated the current sheet thickness to be on the order of several tenths of $r_{\rm E}$. Kaufman (1987) also addressed the question of tail-like magnetic configurations observed near synchronous orbit during disturbed periods and showed, by means of a simple wire model that a dramatic increase of the current in the inner nightside magnetosphere must accompany the sub-storm growth phase. A detailed study by Fairfield et al. (1987) based on AMPTE magnetic field measurements also corroborates the concept of a thin intense tail current sheet deeply embedded into the inner nightside magnetosphere.

- 2. Statistical studies of the average shape and position of the tail-neutral sheet (Russell and Brody, 1967; Fairfield, 1980; Gosling et al., 1986), as well as theoretical considerations (Voigt, 1984) have shown that, for non-zero tilt angle ψ between the z_{GSM} -axis and that of the earth's dipole, the current sheet undergoes a two-dimensional warping. Near the midnight meridian plane, the warping results in a gradual departure of the current sheet from the dipole equatorial plane toward that parallel to the solar-wind stream. This is accompanied by a bending of the sheet in the *YZ* projection in such a way that, for $\psi > 0$, the current surface is raised above the GSM equatorial plane in the central tail region, whereas it is depressed below this plane near the tail flanks (and vice versa for $\psi < 0$).
- 3. Still in early experiments, it has been established that the inner edge of the plasma sheet encircles the earth over a considerable interval of local time (Frank, 1971), and the current flow line pattern in this region should also exhibit an arched configuration, which is manifested in a relatively large value of the B_y -component of the magnetic field observed outside the current sheet in the dawn and dusk sectors (Speiser and Ness, 1967; Fairfield et al., 1987).

Tsyganenko (1989) notes that in his earlier works (Tsyganenko and Usmanov, 1982; Tsyganenko, 1987) no effects of the current sheet warping have been incorporated into the model; the influence of the geo-dipole tilt on the geometry of the tail currents was simulated by a transverse displacement of the sheet as a whole by $z_s = r_{\rm H} \sin \psi$. The largest discrepancies arising due to the inaccuracy of this assumption should be expected in the pre-dawn and post-dusk sectors near the flanks of the tail. An attempt has also been made in these works to take into account the above-mentioned curvilinearity of the current flow lines in the near nightside magnetosphere by introducing the factor f(y) which attenuates the B_x and B_z components toward dawn and dusk flanks. This modification led to a bending of the current flow lines in the necessary direction. However, a significant amount of the current escaped from the sheet due to a j_z component, as a natural consequence of initial simplifying assumption $B_{\nu}^{T} = 0$. In fact, this means that we are unable to extend the sheetlike current structure into the dawn and dusk sectors in the framework of the proposed quasi-two-dimensional tail model. There are reasons to conclude that the above-mentioned shortcomings lead to discrepancies between the model and the average observed magnetic field distribution in the near nightside magnetosphere. The neglect of the effects of the current sheet warping should result in an overestimation of the sheet thickness. The lack of axial symmetry in the current flow line pattern at the nightside, manifested in the absence of B_{y} field component, must distort the distribution of B_z in the region $-10r_{\rm E} \le x_{\rm GSM} \le 0$. Indeed, a comparison of the spatial variation of B_z observed at geosynchronous orbit with that deduced from the Tsyganenko (1987) model has shown that the computed curves exhibit a double-humped shape at the nightside, whereas the ATS-l spacecraft data, as a rule, yield a curve with a single minimum attained near midnight. This feature can be easily understood, taking into account that in most cases the inner edge of the current sheet in the Tsyganenko (1987) model is located closer to the earth than the geosynchronous orbit.

In the Tsyganenko-89 model (Tsyganenko, 1989) a somewhat different approach to the modeling of the intra-magnetospheric current system is developed, which takes into account all the above-mentioned peculiarities of the observed tail current sheet geometry.

7.1.2 Axisymmetric Current Sheet Model and its Modification

First of all, Tsyganenko (1989) considered a problem to find the vector potential induced by an infinitely thin axisymmetric current sheet with a given radial distribution of the transverse component of the magnetic field. In accordance with axial symmetry, he introduced a cylindrical coordinate system (ρ, φ, z) and assumed the vector potential to have only one component $\mathbf{A} = \{0, A(\rho, z), 0\}$. Due to the absence of currents outside the sheet, it will be $\nabla \times \nabla \times \mathbf{A} = 0$ for $z \neq 0$, or

$$\frac{\partial}{\partial \rho} \left(\rho^{-1} \frac{\partial}{\partial \rho} \left(\rho A \right) \right) + \frac{\partial^2 A}{\partial z^2} = 0$$
(7.1)

with a boundary condition at the sheet plane z = 0

$$\rho^{-1}\frac{\partial}{\partial\rho}\left(\rho A\left(\rho,0\right)\right) = B_{z}\left(\rho\right).$$
(7.2)

Separating the variables in Eq. 7.1, Tsyganenko (1989) obtained the general solution as

$$A(\rho, z) = \int_{0}^{\infty} C(K) \exp(-K|z|) J_1(K\rho) K^{1/2} dK, \qquad (7.3)$$

where the function C(K) is determined from the boundary condition described by Eq. 7.2. Substituting Eq. 7.3 into Eq. 7.2, Tsyganenko (1989) found

$$B_{z}(\rho) = \rho^{-1/2} \int_{0}^{\infty} KC(K) J_{0}(K\rho) (K\rho)^{1/2} dK, \qquad (7.4)$$

and, inverting the transformation Eq. 7.4 (Bateman and Erdelyi, M1954), Tsyganenko arrived at

$$KC(K) = \int_{0}^{\infty} B_{z}(\rho) J_{0}(K\rho) (K\rho)^{1/2} \rho^{1/2} d\rho, \qquad (7.5)$$

Inserting in Eq. 7.5 any desirable distribution of $B_z(\rho)$, Tsyganenko could, in principle, find the weight function C(K) which, being then substituted in Eq. 7.3, will give the vector potential $A(\rho, z)$.

Bearing in mind that the final purpose is to solve the inverse problem by means of a least-squares fitting to an extended experimental data set, Tsyganenko had to restrict himself to a limited class of distributions $B_z(\rho)$ which not only have the appropriate behavior but also lead to a relatively simple combination of analytical forms in the expression for $A(\rho, z)$. Perhaps the most compact solution satisfying these requirements corresponds to the following distribution of $B_z(\rho)$:

$$B_z^{(1)}(\rho) \approx \left(a^2 + \rho^2\right)^{-1/2}$$
 (7.6)

which provides the maximal disturbance at the origin and decreases to zero by $\rho \rightarrow \infty$. Substituting Eq. 7.6 into Eq. 7.5 and then into Eq. 7.3 leads (Bateman and Erdelyi, M1954) to the vector potential

$$A^{(1)}(\rho, z) \approx \rho^{-1} \left\{ \left[(a+|z|)^2 + \rho^2 \right]^{1/2} - (a+|z|) \right\}.$$
 (7.7)

Taking the derivatives of Eq. 7.7 by the parameter *a* Tsyganenko obtained a set of independent solutions of Eq. 7.1, corresponding to progressively larger rates of decrease of B_z , and the current density by $\rho \rightarrow \infty$; it is enough to take the first and second derivatives, which yield

$$A^{(2)}(\rho, z) = \frac{\partial A^{(1)}}{\partial a} \approx \rho^{-1} \left\{ 1 - \frac{a + |z|}{\left[(a + |z|)^2 + \rho^2 \right]^{1/2}} \right\},$$
(7.8)

and

$$A^{(3)}(\rho, z) = \frac{\partial A^{(2)}}{\partial a} \approx \rho \left[(a + |z|)^2 + \rho^2 \right]^{-3/2},$$
(7.9)

with the corresponding B_z distributions

$$B_z^{(2)}(\rho,0) \approx \left(a^2 + \rho^2\right)^{-3/2}, \ B_z^{(3)}(\rho,0) \approx \left(\rho^2 - 2a^2\right) \left(a^2 + \rho^2\right)^{-5/2}.$$
 (7.10)

Note that only the third solution, $A^{(3)}(\rho, z)$, yields the current distribution $I(\rho)$ with a finite magnetic moment

$$M = (\pi / c) \int_{0}^{\infty} I(\rho) \rho^{2} \mathrm{d}\rho.$$
(7.11)

This can also be seen from the fact that the potential $A^{(3)}(\rho, z)$ tends to that of a magnetic dipole by $\rho, z \to \infty$. It is also worth noting that $A^{(3)}(\rho, z)$ bears a resemblance to the vector potential of a model ring current introduced in Tsyganenko and Usmanov (1982). Having thus derived a set of solutions for an infinitely thin disk-shaped current, let us extend them to the case of a distributed current sheet having a non-zero scale size of the volume current density profile in the transverse direction. To obtain the potentials corresponding to a sheet with a characteristic half-thickness scale *D*, no more is required than to remove the discontinuity in B_x at z = 0 caused

by the kink of |z| entering in Eqs. 7.7–7.9. The simplest way to do that is to replace |z| by $(z^2 + D^2)^{1/2}$. Strictly speaking, this modification of the vector potential gives rise to a non-zero current in the whole space outside the plane z = 0. However, as a direct calculation of $\nabla \times \nabla \times \mathbf{A}$ shows, the electric current density rapidly goes to zero (as $\propto z^{-2}$) for z > D, so that the layers between the planes $z = \pm D$ and $z = \pm 2D$ contain 75% and 95% of the total current, respectively.

Therefore, Tsyganenko (1989) has to carry out an a posteriori verification of the effects that are expected to be obtained in the electric current pattern. Such a test computation has shown that the necessary modification of the current density distribution can indeed be clearly discernible in the $j = (c/4\pi) \nabla \times \nabla \times \mathbf{A}$ plots. The only limitation here is that the spatial variation of *D* should be rather gradual, to avoid too large artificial currents outside the layer related to the non-constancy of *D*.

The next step is to replace the *z* coordinate in Eqs. 7.7–7.9 by $z' = z - z_s$, where $z_s = z_s(\rho, \varphi)$ or $z_s = z_s(x, y)$ is a function defining the shape of the warped current sheet. In the magnetosphere model described below, the function z_s also includes a parametric dependence on the geo-dipole tilt angle. The magnetic field components B_ρ and B_z , and then the electric current volume density j, can now be determined from the above-derived vector potential (see Fig. 7.1). Figure 7.1 shows radial distributions of j_{φ} (in arbitrary units) in the equatorial plane z = 0, corresponding to the three finite-thickness disk models obtained from Eqs. 7.7–7.9 with a = 1, D = 0.25, where no warping or asymmetry effects had been introduced. The corresponding curves of $B_z(\rho, 0)$ are given in Fig. 7.1 below the horizontal axis. Current densities reach the maximal values at $\rho \approx a$ and decrease to zero by $\rho \rightarrow \infty$ with markedly different rates, which is reflected in a different characteristic broadness of the B_z .



Fig. 7.1 Profiles illustrating the distribution of the volume current density j_{φ} and the transverse component B_z of the magnetic field in the equatorial plane of the axisymmetric model current disks of a finite thickness scale. The characteristic radial scale length, a, and the transverse half-thickness scale, D, equals 1.0 and 0.25, respectively. Both j_{φ} and B_z are scaled in arbitrary units (From Tsyganenko, 1989)

profiles. Making a linear combination of the potentials, corresponding to $A^{(1)} - A^{(3)}$ in Eqs. 7.7–7.9 with different weight coefficients, scale lengths *a*, and half-thickness values *D*, it is possible to obtain a wide variety of magnetic field models corresponding to the finite-thickness warped disklike current distributions. They can be applied to represent the magnetospheric configurations of Jupiter and Saturn. As is shown below, some further modification of the model allows its application to the earth's magnetosphere.

7.1.3 Application to the Earth's Magnetosphere: The Ring Current and the Tail Current Systems

Based on the cumulative body of experimental evidence referred to in Section 7.1.1, Tsyganenko (1989) assumes that the ring current and the tail current form a united sheetlike system in the near nightside magnetosphere, with an arch-shaped configuration of the current flow lines. At relatively small geocentric distances, the current sheet nearly coincides with the dipole equatorial plane and gradually departs from it at larger distances, asymptotically approaching a plane parallel to that of the solar-magnetospheric equator. The model developed below is based on the vector potential representation for the warped current disk matched with the dipole equatorial plane near the earth. For this reason, the solar-magnetic coordinate system (SM) will be used below in defining the current sheet geometry and in the derivation of the expressions for the magnetic field components. The following function was chosen to describe the shape of the nightside current sheet:

$$Z_{s}(x,y,\psi) = 0.5 \operatorname{tg} \psi \left(x + r_{c} - \sqrt{\left(x + r_{c} \right)^{2} + 16} \right) - G \sin \psi \cdot y^{4} \left(y^{4} + L_{y}^{4} \right)^{-1} (7.12)$$

which contains two free parameters, r_c and G. The former is similar to the "hinging distance" (Tsyganenko and Usmanov, 1982) and determines a characteristic distance to a region, where the current sheet warps and departs from the plane $Z_{SM} = 0$. The latter parameter, G, specifies the degree of the transverse bending of the current sheet. The quantity L_y , in the last term in Eq. 7.12 was set at a fixed value $L_y = 10r_E$, in accordance with results of Fairfield (1980) and Gosling et al. (1986). The shape of the model current sheet is displayed in Fig. 7.2, with $\psi = 30^\circ$, $r_c = 8r_E$ and $G = 10r_E$.

The curves $j^{(1)}$ and $j^{(2)}$ in Fig. 7.1 provide a good fit to a characteristic distribution of the current density in the geo-magnetotail plasma sheet (Tsyganenko, 1987). It is thus reasonable to choose the potentials in Eqs. 7.7 and 7.8 as a basis for modeling the tail current system. However, the initial axisymmetric model field (Eqs. 7.7–7.9) extends over all local times and therefore some modification is necessary to remove or redistribute the current at the dayside and to confine the main part of the current sheet to the magnetotail domain. In the proposed model it is achieved,



Fig. 7.2 Illustrating the geometry of the warped model current sheet in two cross sections, according to Eq. 7.13, for $\psi = 30^\circ$, $r_c = 8r_E$, $G = 10r_E$, $L_v = 10r_E$ (From Tsyganenko, 1989)

firstly, by a special choice of the function D(x, y) defining the current sheet thickness profile. Namely, the sheet is supposed to become thicker toward the dayside and toward the flanks of the tail. Secondly, the vector potential of the disk is multiplied by a factor W(x, y), which equals unity in the central tail region $(x \le -10r_E, y \approx 0)$ and smoothly drops off to zero towards the sub-solar magnetopause region, as well as for $|y| \to \infty$. As the direct computation of $\nabla \times \mathbf{B}$ has shown, this results in such a redistribution of the initially axisymmetric current flow pattern, that both the total current and the gradient of the volume current density are depressed throughout the dayside magnetosphere. In the nightside region, the current is localized within a thin sheet centered at the warped surface $z = z_s(x, y, \psi)$.

As for modeling the ring current contribution, it is most appropriate to proceed from the potential $A^{(3)}$ in Eq. 7.9, since it provides the most localized current density profile with the highest rate of decrease toward larger distances. Possible effects of the day–night asymmetry are incorporated in the ring current model by allowing the current sheet thickness to be a function of X_{SM} , like in the tail-sheet model.

The results of computation of the model parameters from the experimental data has shown that for all model versions with $K_p < 4^-$, a small "island" with a slightly negative B_z on the order of -0.5 ± 1.0 nT is obtained persistently in the central part of the nightside current sheet $(-16r_E \ge x_{GSM} \ge -20r_E, |y_{GSM}| \le 4r_E)$. A direct inspection of data in this region, as well as statistical results by Fairfield (1986), lead to the conclusion that it is most likely an artifact of the extreme sensitivity of the B_z component in the sheet to the details of the current density distribution along the tail (see also the discussion of difficulties of the current "slab" models in Stem, 1987). A point here is that the B_z experimental values in the equatorial region are relatively small and hence the least-square values of the model parameters are determined mainly by the B_x distribution in the tail lobes.

Final expressions for the azimuthal component of the vector potential corresponding to the tail current sheet (labeled by the index T) and the ring current (index RC) are as follows (Tsyganenko, 1989):

$$A^{(T)} = \frac{W(x,y)}{S_T + a_T + \xi_T} \left(C_1 + \frac{C_2}{S_T} \right), A^{(RC)} = C_3 \rho S_{RC}^{-3},$$
(7.13)

where

$$W(x,y) = 0.5 \left(1 - \frac{x - x_o}{\left[(x - x_o)^2 + D_x^2\right]^{1/2}}\right) \left(1 + y^2 / D_y^2\right)^{-1},$$

$$S_{T,RC} = \sqrt{\rho^2 + (a_{T,RC} + \xi_{T,RC})^2}, \ \xi_{T,RC} = \sqrt{z_r^2 + D_{T,RC}^2}, \ z_r = z - z_s(x,y,\psi),$$

$$D_T = D_o + \delta y^2 + \gamma_T h_T(x) + \gamma_1 h_1(x), \ D_{RC} = D_o + \delta y^2 + \gamma_{RC} h_{RC}(x) + \gamma_1 h_1(x),$$

$$h_{T,RC} = 0.5 \left[1 + x \left(x^2 + L_{T,RC}^2\right)^{-1/2}\right], \ h_1 = 0.5 \left[1 + (x + 16) \left((x + 16)^2 + 36\right)^{-1/2}\right].$$

(7.14)

The magnetic field components are easily obtained from Eq. 7.13 as follows:

$$B_x^{(T)} = Q_T x z_r, \ B_y^{(T)} = Q_T y z_r, \ B_z^{(T)} = \frac{W(x,y)}{S_T} \left(C_1 + C_2 \frac{a_T + \xi_T}{S_T^2} \right) + \left(C_1 + \frac{C_2}{S_T} \right) \\ \times \frac{x \frac{\partial W}{\partial x} + y \frac{\partial W}{\partial y}}{S_T + a_T + \xi_T} + B_x^{(T)} \frac{\partial z_s}{\partial x} + B_y^{(T)} \frac{\partial z_s}{\partial y} - Q_T D_T \left(x \frac{\partial D_T}{\partial x} + y \frac{\partial D_T}{\partial y} \right), \ (7.15)$$

where

$$Q_T = \frac{W(x,y)}{S_T \xi_T} \left(\frac{C_1}{S_T + a_T + \xi_T} + \frac{C_2}{S_T^2} \right),$$
(7.16)

and

$$B_{x}^{(RC)} = Q_{RC}xz_{r}, B_{y}^{(RC)} = Q_{RCr}^{yz}, B_{z}^{(RC)} = C_{3}\frac{2(a_{RC} + \xi_{RC})^{2} - \rho^{2}}{S_{RC}^{5}} + B_{x}^{(RC)}\frac{\partial z_{s}}{\partial x} + B_{y}^{(RC)}\frac{\partial z_{s}}{\partial y} - Q_{RC}D_{RC}\frac{\partial D_{RC}}{\partial x},$$
(7.17)

where

$$Q_{RC} = 3C_3 \xi_{RC}^{-1} S_{RC}^{-5} (a_{RC} + \xi_{RC}) x z_r$$
(7.18)

According to Tsyganenko (1989), coefficients C_1 , C_2 , and C_3 specify the contribution to the total magnetic field from three terms, corresponding to Eqs. 7.7–7.9 and having different decrease rates in the limit $\rho \rightarrow \infty$. Among the nonlinear parameters of the model are the following: a_T and a_{RC} , the radial scale lengths, which define the geocentric distance to the current density maxima; x_o , the coordinate defining the location of the region of steepest decrease of the "truncation factor" W(x,y); D_x and D_y , the scale lengths corresponding to variations of W(x,y) along x- and y-axes; D_o , the half-thickness of the current sheet in the central magnetotail region; γ_T and γ_{RC} , the increments of the current sheet thickness between the nightside and dayside regions; L_T and L_{RC} , the scale distances for the functions h_T and h_{RC} , varying monotonically between zero and unity; δ , the factor defining the rate of the tail current sheet thickening toward its flanks. The model also contains two nonlinear parameters r_c and G, which define the shape of the warped current sheet given by Eq. 7.12. The additional term, $\gamma_1 h_1$ in the expressions for D_T and D_{RC} , provides a gradual thickening of the sheet in the tailward direction beyond $x_{\text{GSM}} \approx -15r_{\text{E}}$ and eliminates the above-mentioned B_z reversals in the near magnetotail. Not all these parameters were treated as variable ones in fitting the model to the experimental data sets, only those which possess a sufficient degree of independence of each other.

This means, according to Tsyganenko (1989), those variations of these parameters about their initial tentative values should induce an essentially different redistribution of the model magnetic field. For example, it is a priori clear that changes in the parameters γ_T and γ_{RC} will not lead to a significant variation of the magnetic field in the nightside region, whereas at the dayside they yield nearly the same effects. For this reason, one of them, γ_T , has been fixed and the other, γ_{RC} , has been left as a free parameter. From similar a priori considerations, as well as from the obtained a posteriori estimates of the parameter errors and trends in their behavior in the course of successive iterations, Tsyganenko (1989) finally decided to fix the following parameters by the values: $L_v = 10$, $D_x = 13$, $L_{RC} = 5$, $L_T = 6.3$, $\gamma_T = 4$, $\delta = 0.01$, $\gamma_1 = 1$. The following parameters were retained as free variables: coefficients C_1 , C_2 , C_3 , and the nonlinear parameters a_T , a_{RC} , x_o , D_v , D_o , γ_{RC} , r_H , G. It should be emphasized once again that the nightside current sheet in this model has no abrupt inner edge. As can be seen from Fig. 7.1, it rather penetrates inward up to a very close geocentric distance, the current density varying here linearly with r. In principle, by adding more terms of the type Eqs. 7.7–7.9 to the vector potential, it is possible to suppress the current in the innermost extraterrestrial region or to simulate the eastward diamagnetic current at the inner boundary of the radiation belt. However, an attempt to include these details in the model did not lead to any successful results; the most likely reasons are as follows:

- 1. A relatively high level of "noise" in the data, which smears out any fine structure in the field distribution
- 2. A relatively low density of the data points in the low-altitude region of the magnetosphere at $4r_E \le r \le 5r_E$ with the absence of measurements at closer distances.

7.1.4 Contribution from the Magnetospheric Boundary Sources

As pointed out in Tsyganenko (1987), to obtain a correct distribution of both B_x and B_z in the model magnetospheric tail, it is necessary to incorporate the effects from the return current closing the central tail current sheet across the high-latitude magnetopause regions and enveloping the lobes. In the considered model Tsyganenko-89, these sources are simulated by a pair of planar current sheets parallel to the GSM equatorial plane and located at $z_c = +r_T$, with $r_T = 30r_E$. The contribution from each sheet was represented by the vector potential of the $A^{(1)}$ type in Eq. 7.7 with a "truncation factor" $W_c(x, y)$ similar to that in the central sheet model. Since both sheets are located outside the modeling region, it is possible to make simplifying assumptions a = 0 and D = 0. In contrast with Tsyganenko (1987), no constraint conditions have been imposed on the total current in both sheets, which would relate it to the total central sheet currents. Rather, it was assumed that the contribution from 7 Magnetospheric Models and their Checking by Cosmic Rays

the return current can be divided into two terms, symmetrical and antisymmetrical with respect to the dipole tilt angle, ψ . The first term represents the main part of the field corresponding to perpendicular geo-dipole orientation, and the second one models the effect of asymmetry between the northern and southern lobes arising due to the dipole tilt. Final expressions for the return current contribution are as follows:

$$B_{x,y,z}^{c} = C_4 \left(F_{x,y,z}^+ + F_{x,y,z}^- \right) + C_5 \left(F_{x,y,z}^+ - F_{x,y,z}^- \right) \sin \psi, \tag{7.19}$$

where

$$\begin{cases} F_{x}^{\pm} \\ F_{y}^{\pm} \end{cases} = \pm \frac{W_{c}(x,y)}{S^{\pm} \left[S^{\pm} \pm (z \pm r_{T})\right]} \times \begin{cases} x \\ y \end{cases}, F_{z}^{\pm} = \frac{W_{c}(x,y)}{S^{\pm}} + \frac{\left(x \frac{\partial W_{c}}{\partial x} + y \frac{\partial W_{c}}{\partial y}\right)}{S^{\pm} \pm (z \pm r_{T})},$$
$$S^{\pm} = \left[(z \pm r_{T})^{2} + x^{2} + y^{2}\right]^{1/2}, W_{c}(x,y) = \frac{1 - \frac{x - x_{oc}}{\left[(x - x_{oc})^{2} + L_{xc}^{2}\right]^{1/2}}}{2\left(1 + y^{2} / D_{yc}^{2}\right)}.$$
(7.20)

Note that x, y, z here are the solar-magnetospheric coordinates, rather than solarmagnetic ones, as in Eqs. 7.13–7.17. Due to the relatively small contribution of these sources to the total field, only coefficients C_4 and C_5 were assigned to be variable parameters. All the nonlinear parameters were fixed at values $r_T = 30$, $x_{oc} = 4$, $L_{xc}^2 = 50$, $D_{yc} = 20$, chosen from a priori considerations and preliminary test runs.

A contribution from the Chapman–Ferraro currents at the magnetopause and that from the rest of the intra-magnetospheric sources (including field-aligned currents (FACs)) was chosen in the described model Tsyganenko-89 just as the in Tsyganenko (1987) "truncated" version:

$$B_x^{(M)} = \exp(x/\Delta x) \left[C_6 z \cos \psi + (C_7 + C_8 y^2 + C_9 z^2) \sin \psi \right], B_y^{(M)} = \exp(x/\Delta x) \\ \times \left[C_{10} y z \cos \psi + (C_{11} y + C_{12} y^3 + C_{13} y z^2) \sin \psi \right], B_z^{(M)} = \exp(x/\Delta x) \\ \times \left[(C_{14} + C_{15} y^2 + C_{16} z^2) \cos \psi + (C_{17} z + C_{18} z y^2 + C_{19} z^3) \sin \psi \right], \quad (7.21)$$

where Δx is a characteristic scale length along the sun–earth direction. The last four coefficients $C_{16} - C_{19}$ are not independent, since they are expressed through the first ones in accordance with the equation $\nabla \cdot \mathbf{B} = 0$. Hence, these terms yield 11 free parameters, namely, Δx and $C_6 - C_{15}$.

7.1.5 Analysis of the Model's Parameters Depending on K_p

Numerical fitting in Tsyganenko (1989) of the model's parameters to the measured magnetic field has been carried out by means of the same algorithms and using the same data as in Tsyganenko (1987). The merged spacecraft data set used as the experimental base for the modeling contains 36,682 vector averages of the magnetospheric field measured during the period from 1966 to 1980 aboard eight

IMP and two HEOS satellites in the geocentric distance range from $4r_{\rm E}$ to $70r_{\rm E}$. Computations were carried out for a series of data subsets created by sorting out the measurements corresponding to selected intervals of the geomagnetic activity indices (K_p) . In Tsyganenko (1989), the same six data subsets have been used, as in the Tsyganenko (1987) "long" model version, namely, $K_p = 0, 0^+$; $K_p = 1^-, 1,$ 1^+ ; $K_p = 2^-$, 2, 2^+ ; $K_p = 3^-$, 3, 3^+ ; $K_p = 4^-$, 4, 4^+ ; and $K_p \ge 5^-$. The only difference is that in Tsyganenko (1987) a consolidation procedure had been applied to the second, third, and fourth subsets, in order to reduce excessively large numbers of data points. In Tsyganenko (1989), it was decided to abandon this procedure; as a result, an insignificant increase in the average external field values occurred in these three subsets. The model parameters listed in Section 7.1.3 were found for each data subset by means of an iterative algorithm incorporating a standard least-squares technique for computing the linear parameters and the Newton-Lecam-Marquardt method for the nonlinear ones. It was also possible to estimate the errors of the parameter values obtained, as well as to assess the degree of inter-correlation between them. The calculated model parameters are listed in Table A7.1; the columns, from left to right, correspond to progressively larger values of the K_p index.

As can be seen from Table A7.1, the three coefficients C_1 , C_2 , and C_5 , which define the current distribution in the central current sheet, show in general an orderly increase with the K_p -index. The coefficient C_1 corresponding to the most slowly varying part of the vector potential and current, changes in a somewhat more chaotically manner, than C_2 and C_5 do, but the total model field generally shows a more regular dependence on K_p since the fluctuations in its separate terms are approximately cancelled by each other. Note also that the most dramatic increase is observed in the coefficient C_5 corresponding to the most localized part of the central sheet current. Hence, the increase in the disturbance level is manifested in the increase of the tail current magnitude mainly in its innermost region, in accordance with the results of Tsyganenko (1987). The coefficient C_3 defining the symmetric part of the closure current contribution also grows rapidly with K_p , but the amplitude of the antisymmetric term, C_4 , exhibits a more complex behavior.

The non-monotonic abrupt changes of C_4 are reduced by other terms in the total field; this is evident, for example, from a distinct correlation between the coefficients C_4 and C_{17} , corresponding to the terms with the same type of symmetry as in the B_z component. The coefficients $C_6 - C_{19}$ of the expansions in Eq. 7.20 have the same order of magnitude and reveal basically the same dependence on K_p as the corresponding coefficients $a_1 - a_6$ in the "truncated" model (Tsyganenko, 1987).

With regard to the nonlinear parameters, the most conspicuous feature is a rapid monotonic decrease of the current sheet half-thickness *D* with increasing K_p , from $D \approx 2.1$ for $K_p = 0$, 0^+ up to $D \approx 0.3$ for $K_p \ge 5^-$. In order to clarify this result, Tsyganenko (1989) noted that the thinning of the model current sheet in the near magnetotail should, in principle, be manifested not only in a thinning of the B_x component reversal region, but also in an increase of the magnitude of B_z depression in the whole region adjacent to the inner part of the current sheet. Since the density of used experimental data points in this region is rather low and the actual current sheet location in the Z direction can fluctuate considerably from case to case, then we have to conclude that the obtained close and clear relationship between D and K_p , as well as such a small value of D for disturbed conditions, are related mainly to the peculiarities of the B_z distribution, rather than to the extremely regular pattern of the B_x reversals.

The next feature of the current sheet geometry evident from Table A7.1 consists in a distinctly growing asymmetry between the dayside and nightside sector with increasing K_p . This asymmetry is defined by the parameter γ_{RC} which appears to be slightly negative for $K_p = 0$, 0^+ and then grows almost monotonically up to ≈ 6.5 by $K_p \ge 5^-$. Therefore, thinning of the sheet at the nightside is accompanied by its considerable thickening at the dayside, with an increasing disturbance level. The quantity a_{RC} defining the characteristic scale radius of the ring current also decreases monotonically, although within a rather limited range from ≈ 8.2 in very quiet conditions up to ≈ 5.8 in the most disturbed conditions. A similar quantity a_T corresponding to the more slowly varying tail field terms shows a gradual increase with K_p , though also within a narrow interval between 13.6 and 15.9.

Of the two parameters, r_c and G, which determine the effects of the current sheet warping, only the last one exhibits a pronounced change, increasing from 3.8 to 9.1 with growing K_p . The former parameter r_c varies between 9.1 and 10.5. Thus, the influence of the disturbance level is mainly manifested in the degree of the transverse bending of the current sheet. Under quiet conditions, the amplitude of diurnal and seasonal motion of the current sheet with respect to the GSM equatorial plane shows a relatively weak dependence on Y_{GSM} . During disturbed conditions, the central part of the sheet oscillates with nearly the same amplitude, whereas toward the flanks the displacement tends to zero or even becomes negative. With regard to the parameter $r_{\rm c}$, the observed lack of its dependence on $K_{\rm p}$ (in fact, $r_{\rm c}$ even grows slightly with $K_{\rm p}$) is in obvious disagreement with the statistical studies of Tsyganenko and Usmanov (1982) and Tsyganenko (1987), in which a clear trend of the "hinging distance" $r_{\rm H}$ to decrease with increasing $K_{\rm p}$ -index had been revealed. However, since planar current sheet models had been used in that work, the obtained $r_{\rm H}$ values correspond, in fact, to the spatially averaged amplitude of the current sheet transverse motion, which can be significantly less than the actual displacement near the midnight meridian, due to the bending of the sheet flanks toward the equatorial plane. Tsyganenko (1989) noted that typical $r_{\rm H}$ values obtained in the papers by Tsyganenko and Usmanov (1982), and Tsyganenko (1987) are, indeed, by a factor 1.2–2.0 less than r_c values in Tsyganenko (1989). The observed increase of G with $K_{\rm p}$ is equivalent to a decrease of the average amplitude of the current sheet displacement manifested in a corresponding decrease of the "effective" hinging distance $r_{\rm H}$ reported in Tsyganenko and Usmanov (1982), and Tsyganenko (1987).

The parameter x_o defining the shift of the "truncation factor" W(x,y) along the *x*-axis from the origin grows almost steadily with increasing K_p , which reflects a general enhancement of the intra-magnetospheric currents in the dayside sector. The variation of the scale lengths Δx and D_y with K_p bears a qualitative resemblance with that obtained in Tsyganenko and Usmanov (1982), though the numerical values are in Tsyganenko (1989) significantly larger, due to the adopted modifications of the model functions and a more extended modeling region.

7.1.6 Model of Magnetic Field Distribution and Field-Line Configurations

Tsyganenko (1989) noted that the general comparison with the results of Tsyganenko and Usmanov (1982), and Tsyganenko (1987) show that the most distinct changes in the model magnetic field distribution are observed in the night-side sector. It is just what was expected, since major improvements of the model concern the tail current and the nightside part of the ring current. The main result here is that a significantly more depressed field, and hence a more stretched force line pattern, is obtained in the near magnetotail region for all K_p intervals, the most dramatic changes being observed for the highest level of disturbance.

Figure 7.3 gives a family of contours of constant B_z corresponding to the net contribution from all external model field sources in the plane $z_{\text{GSM}} = 0$, for three levels of disturbance, $K_p = 0$, 0^+ , $K_p = 3^-$, 3, 3^+ , and $K_p \ge 5^-$.

The main tendency evident from the maps in Fig. 7.3 is a significant deepening of the B_z depression in the near-earth region, the minima of ΔB being observed in all cases in the midnight sector at $z_{\text{GSM}} \approx -2.5r_{\text{E}}$. However, the real location of these minima and corresponding ΔB_{min} values may be somewhat different from the model results, and the whole structure of the external field and current distribution in the innermost near-earth region can be significantly more complex; used data-set coverage does not allow one to resolve finer details, since the experimental points are absent inside $r \approx (4-5) r_{\text{E}}$. Nevertheless, the obtained ΔB_{\min} values seem to be in line with the existing measurements made at closer geocentric distances.

According to the results of the AMPTE magnetic field experiment (Fairfield et al., 1987), a typical ΔB value inside $r \approx 5r_{\rm E}$ in the near-equatorial nightside region is about $\Delta B \approx -80\,{\rm nT}$ for $K_{\rm p} > 3^+$. Since the number of data set points corresponding to a given $K_{\rm p}$ value drops off rapidly with increasing $K_{\rm p}$, the main part of the measurements taken by $K_{\rm p} > 3^+$ falls into the interval $K_{\rm p} = 4^-$, 4, 4⁺. Computation using the Tsyganenko-89 model with a corresponding set of parameters yields the value $\Delta B = -87\,{\rm nT}$ for $x_{\rm GSM} = -4r_{\rm E}$; a minimal value $\Delta B_{\rm min} \approx -103\,{\rm nT}$ is attained at $x_{\rm GSM} = -2.5r_{\rm E}$ in good agreement with the above-mentioned estimate by Fairfield et al. (1987).

Another tendency, also clearly seen in Fig. 7.3, is that a decrease in B_z occurs predominantly within the near-tail domain with $x_{\text{GSM}} \ge -12r_{\text{E}}$; at greater distances a slight increase of B_z with K_p is evident, manifested in an earthward shift of the $K_p = 0$ contour. This feature had also been noted in Tsyganenko (1987) and was revealed in a number of preliminary test versions of the model, as well as in a direct inspection of the averages calculated from the experimental B_z values inside the plasma sheet region. Therefore, Tsyganenko (1989) is inclined to conclude that this is scarcely a modeling artifact but, rather, a manifestation of a real average increase of the tail magnetic flux connection through the neutral sheet during disturbed periods.

Figure 7.4 illustrates some results of a comparison of the model field with the data from other spacecraft measurements, in the format of plots of the B_z component of



Fig. 7.3 Three families of equal intensity contours of the external model field B_z in the GSM equatorial plane, for zero tilt angle $\psi = 0^\circ$, corresponding to three levels of geomagnetic disturbance (From Tsyganenko, 1989)

the external field (geo-dipole contribution excluded) near the midnight point of the synchronous orbit ($r = 6.6 r_E$) versus K_p -index. The open circles represent the B_z values computed using the present model and the triangles correspond to the "truncated" version of the Tsyganenko (1987) model. The solid circles give the average B_z values measured onboard the ATS-1 satellite in 1967 (a total of 232 hourly averages) and vertical bars show the corresponding r.m.s. deviation for each point.

As seen from the plots in Fig. 7.4, the Tsyganenko-89 model yields a significantly more depressed field than that of Tsyganenko (1987), but the ATS-1 curve is still \approx 10nT lower. What is the cause of such a discrepancy remains yet unclear, but Tsyganenko (1989) have to bear in mind that the *H*-component values in the ATS-1



Fig. 7.4 Plots of the B_z component of the external field near the midnight point of the geosynchronous orbit vs K_p . Open circles and triangles correspond to the Tsyganenko-89 model and to the previous version (Tsyganenko, 1987), respectively. Solid circles, dashed line, and dashed-dotted line represent the average values obtained from ATS-1, AMPTE and OGO-3,-5 spacecraft measurements, respectively (From Tsyganenko, 1989)

data set were initially corrected by $\Delta H = -20 \,\text{nT}$, with the purpose of eliminating the positive bias mentioned in the work by Coleman and McPherron (1976) and related to uncertainties in evaluating the spacecraft magnetic field. The value of this additive correction had been specified, in particular, on the basis of work of Sergeev et al. (1983), in which it was shown that the observed latitude Λ_i , of the isotropic precipitation boundary for energetic protons show a very good correlation with the H_{ATS} measured at the midnight segment of the ATS-1 orbit.

The correction of $\Delta H \approx -20 \,\text{nT}$ appeared necessary to obtain the best fit of the experimental dependence of Λ_i , on H_{ATS} to that obtained from calculations of the latitudes of the non-adiabatic particle scattering boundaries, based on the Tsyganenko and Usmanov (1983) magnetic field model. Thus, the above estimate for ΔH is model-dependent and hence may well be in error of $\approx l0 \,\text{nT}$.

Dashed and dashed-dotted lines in Fig. 7.4 represent the results of the AMPTE (Fairfield et al., 1987) and OGO (Sugiura and Poros, 1973) measurements at $x \approx -6.6r_{\rm E}$, respectively. For small $K_{\rm p}$ values, the Tsyganenko-89 model shows a good agreement with the data, while for $K_{\rm p} > 3^+$ it provides a more depressed B_z than that observed by the spacecraft.

7.1.7 Local Time-Dependence of the Average Inclination Angles

It is also of much interest to use the statistical results by Lin and Barfield (1984) on the local time-dependence of the measured average inclination angles at the geosynchronous orbit as an independent experimental test for the Tsyganenko-89 model. For this purpose the average values of the inclination angle, *I*, have been computed over a 12-month period for every hour of local time at the position of the GOES-1 spacecraft, using the model distribution of the external magnetic field for three levels of the K_p -index, namely, $K_p = 1^-, 1, 1^+, K_p = 3^-, 3, 3^+$, and $K_p \ge 5^-$. These intervals of K_p most closely correspond to those chosen by Lin and Barfield (1984): respectively, 0–2, 2–4, 4–9, and, hence, are the most appropriate for comparison.

The three panels of Fig. 7.5, from the bottom to the top, display the inclination dependence on the local time, for the progressively higher levels of the $K_{\rm p}$ -index. The upper histograms in all three panels show the experimental results of GOES measurements of Lin and Barfield (1984). Smooth curves represent the modeling results. The dotted curves in the top and bottom panels correspond to the Mead and Fairfield (1975) model. The broken lines were obtained from the Tsyganenko (1987) model, showing better agreement with the GOES histograms. The best results are given by the Tsyganenko (1989) model (solid curves), which predicts the inclination angles near midnight much closer to the experimental values. However, there still remains a disagreement in that all model curves lie below the GOES histograms. The largest discrepancies of about 15° correspond to the highest level of geomagnetic disturbance (upper panel) and are localized in the evening sector, showing a significant dawn-dusk asymmetry of the field line stretching, which is much smaller for a moderately disturbed magnetosphere and almost completely vanishes for the lowest activity interval $K_p = 0-2$. As follows from Figs. 7.4 and 7.5, the Tsyganenko (1989) model provides an improved representation of the geomagnetic field in the lowlatitude nightside magnetosphere, despite the improvements being hardly visible in the overall r.m.s. residuals.

7.1.8 Distribution of Electric Current Density

Figure 7.6 shows a family of contours of constant volume density of the electric current computed from the model magnetic field as $\mathbf{j} = (c/4\pi) \nabla \times \mathbf{B}$ in the midday-midnight meridian plane. The pattern corresponds to the moderately disturbed conditions ($K_p = 4^-, 4, 4^+$) with the geo-dipole tilt angle close to its maximal value $\psi = 34.4^\circ$, and clearly displays the expected warping of the tail current sheet.

A small residual current density outside the central sheet region is in the order of 10^{-10} A.m⁻² and is partly induced by the terms in Eq. 7.21, since it was not imposed on them the condition $\nabla \times \mathbf{B} = 0$. A similar pattern of the j_y distribution in the tail cross section at $x_{\text{GSM}} = -10r_{\text{E}}$ also reveals the expected warping of the



Fig. 7.5 Comparison of the inclination angles *I* measured by GOES-2 spacecraft (Lin and Barfield, 1984) with those predicted by three models for different local times. The three panels, from the *bottom* to the *top*, correspond to progressively higher K_p levels. The *upper* histograms in each panel show the average distributions of the inclination angle measured by GOES-2 (radial distance $r \approx 6.6 r_E$, dipole latitude $\phi = 9.6^\circ$) versus local time. Dotted lines, broken lines, and smooth solid lines correspond to the Mead and Fairfield (1975) model, the model by Tsyganenko (1987), and the Tsyganenko (1989) model, respectively (From Tsyganenko, 1989)

model current sheet in the *Y*–*Z* plane, as shown in Fig. 7.7. Two layers of return currents located at $z = \pm 30r_E$ are not shown, being outside the frames of this figure, but it is just there that the most part of the equatorial current is closed.



Fig. 7.6 A family of contours $j_y = \text{const}$ in the midday–midnight meridian plane, obtained by direct computation of $\nabla \times \mathbf{B}$ for the moderately disturbed set of the model's parameters ($K_p = 4^-$, 4, 4⁺) and $\psi = 34.4^\circ$. The lines are labeled in units $10^{-10} \text{ A.m}^{-2}$. Note the warping of the current sheet and a significant day–night asymmetry of the current density distribution. The return current layers located at $z = \pm 30 r_{\rm E}$ lie outside the frame of this picture (From Tsyganenko, 1989).



Fig. 7.7 A family of contours of $j_y = \text{const}$ in the magnetotail cross section $x_{\text{GSM}} = -10r_{\text{E}}$ showing the warping effects in the Y - Z plane (From Tsyganenko, 1989)

7.1.9 The Model Field-Line Configurations for Several K_p Intervals

Figures 7.8–7.12 display the model field-line configurations for several K_p intervals. As already noted above, the model shows significantly more stretched field lines at the nightside, in comparison with earlier model versions. Thus, for the highest disturbance level with $K_p \ge 5^-$, the line starting at 66° dipole latitude from the earth has its equatorial crossing point at $r_c = 30r_E$, while in the Tsyganenko (1987) model about three times lesser r_c was obtained for the same K_p conditions.



Fig. 7.8 Field-line pattern in the noon-midnight meridian plane, corresponding to very quiet conditions $(K_p = 0, 0^+)$. Field-lines start from the Earth at latitudes 2° apart, beginning from 60°. (From Tsyganenko, 1989)



Fig. 7.9 Field line pattern for average conditions characterized by $K_p = 2^-$, 2, 2⁺ (From Tsyganenko, 1989)


Fig. 7.10 The same, as in Fig. 7.9, for a tilted geo-dipole with $\psi = 30^{\circ}$ (From Tsyganenko, 1989)



Fig. 7.11 Field-line pattern for a disturbed magnetosphere ($K_p = 4^-, 4, 4^+$) (From Tsyganenko, 1989)



Fig. 7.12 Field-line pattern for a strongly disturbed magnetosphere ($K_p > 5^-$) (From Tsyganenko, 1989)

7.1.10 Summary of Main Results and Model Developing

Tsyganenko (1989) developed an improved quantitative representation of the magnetic field in the geo-magnetosphere. The Tsyganenko-89 model, as it is now called in scientific literature, takes into account the effect of warping the tail current sheet in two dimensions due to the geo-dipole tilt, as well as spatial variations of the current sheet thickness along the sun-earth and dawn-dusk directions. The corresponding analytic forms for the magnetic field components have been obtained using an indirect approach in a two-stage procedure. First of all, a simple axisymmetric infinitely thin current disk model with different rates of current density decreasing in the radial direction is derived. The next step consists of a formal modification of the obtained expressions for the vector potential, which results in a transverse broadening of the initially thin current sheet and incorporates an account for the sheet warping. A truncation factor is also introduced, with the aim to simulate the finite extension of the current system in the dawn-dusk direction, as well as its day-night asymmetry. Based on the proposed representation and the IMP and HEOS spacecraft data pool, a series of magnetospheric models are generated, giving a quantitative description of the average magnetic field configuration for different disturbance levels. A comparison of the magnetic field distributions predicted by the model and those measured at geosynchronous orbit has been carried out. Tsyganenko (1989) noted that the average configuration of the tail field lines crossing the plasma sheet and their mapping onto the earth's surface is very sensitive to the details of the current distribution. In view of a relatively low density of the data points in the near-earth region and at low latitudes in the near magnetotail, further work in this direction should be done, based on extended data sets.

The development of this research was done in Tsyganenko and Stern (1996). Ouantitative models are developed for representing the global distribution of the average magnetic field produced by Regions 1 and 2 of the Birkeland current systems. The problem is solved in the four following steps: (1) constructing a realistic tiltdependent model of the Birkeland current sheets, based on the formalism of Euler potentials; (2) numerically computing their field at a large number of points within the modeling region; (3) finding a best-fit analytical approximation for that field; and (4) adding a current-free shielding field which confines the Birkeland field within the model magnetopause. At low altitudes, the model FACs reach the ionosphere along eccentric ovals, which fit the observed Regions 1 and 2 zones of Iijima and Potemra (1982), and they continue there as horizontal currents. At larger distances, the nightside Region 1 currents map to the plasma sheet boundary layer and are then diverted toward the tail flanks, while currents in the dawn-dusk and dayside sectors connect directly to the higher-latitude magnetopause. The Region 2 current closes azimuthally near the equator, forming a spread-out PRC system. The model includes a dependence of the current flow geometry on the geo-dipole tilt and is intended for inclusion in a global data-based representation of the magnetospheric field, parameterized by the solar wind characteristics.

7.2 Magnetospheric Configurations from a High-Resolution Data-Based Magnetic Field Model

7.2.1 The Matter of Problem

Tsyganenko and Sitnov (2007) present first results of the magnetospheric magnetic field modeling, based on large sets of spacecraft data and a high-resolution expansion for the field of equatorial currents. In this approach, the field is expanded into a sum of orthogonal basis functions of different scales, capable of reproducing arbitrary radial and azimuthal variations of the geomagnetic field, including its noon–midnight and dawn-dusk asymmetries. Combined with the existing method to model the global field of Birkeland currents, the new approach offers a natural way to consistently represent the field of both the tail and symmetric ring currents (SRCs)/PRCs. The proposed technique is particularly effective in the modeling of the inner magnetosphere, a stumbling block for the first-principle approaches. The new model has been fitted to various subsets of data from Geotail, Polar, Cluster, IMP-8, and GOES-8, GOES-9, GOES-10, and GOES-12 spacecrafts, corresponding to different solar- and magnetic-activity levels, solar-wind IMF conditions, and magnetic-storm phases. The obtained maps of the magnetic field reproduce most basic features of the magnetospheric structure, their dependence on the geomagnetic

activity and interplanetary conditions, as well as characteristic changes associated with the main and recovery phases of magnetic storms.

As Tsyganenko and Sitnov (2007) noted, the ultimate goal of empirical modeling is to extract maximum meaningful information on the modeled object from a given body of data. In most situations, the amount of that information critically depends on the coverage of the object by the data in space and time. Sparse and/or non-uniform coverage allows one to use rather simple models with a few degrees of freedom, replicating only some basic features of the object and its response to external input. In the specific case of the earth's magnetosphere, the lack of in situ spacecraft data as well as the shortage of continuous concurrent data from solar-wind monitors during the 1970s and 1980s was the main factor that limited the resolution of early models, constructed from a few "custom-made" modules representing contributions from major magnetospheric current systems (see Tsyganenko, 1990 for a review).

Tsyganenko and Sitnov (2007) underlined that the situation has changed dramatically since: (1) during the last decade the magnetospheric data pool was greatly expanded owing to almost continuous monitoring of the solar wind and IMF by spacecrafts WIND, ACE, and IMP-8; (2) a very dense coverage of the nearequatorial magnetosphere at $10r_E < r < 30r_E$ by nearly 14 years worth of Geotail data; and (3) large amounts of low- and high-latitude data from GOES-8, GOES-9, GOES-10, GOES-12, and Polar satellites. Such a wealth of data offered an attractive opportunity to study in much more detail the magnetospheric structure and its response to external conditions.

According to Tsyganenko and Sitnov (2007), most of the electric current associated with the observed configuration of the distant geomagnetic field concentrates at low latitudes, where the plasma beta parameter rises to its maximal values. From the modeling perspective, these currents can be viewed as a single large-scale equatorial system, including the ring current in the inner magnetosphere and the cross-tail current sheet at larger distances. The second major component, substantially different from the first one, is the system of FACs, including those associated with the storm-time PRC. Their essential role is to directly transfer the solar-wind momentum from the magnetosheath to the high-latitude ionosphere (Region 1 FAC) and to divert the equatorial currents to higher latitudes, providing the electrodynamical coupling of the plasma sheet with the auroral zone (Region 2 FAC and the PRC). The third component is the magnetopause current system, whose role is to confine the total field within the magnetospheric boundary. Tsyganenko and Sitnov (2007) develop a new approach to consistently unify all the three groups of sources into a single model and demonstrate its feasibility by deriving from data sample geomagnetic configurations, corresponding to different conditions in the solar wind and in the magnetosphere.

7.2.2 Modeling Equatorial Current System: Main Approach

Tsyganenko and Sitnov (2007) noted that in the recent models (Tsyganenko, 1995, 1996, 2002a, b; Tsyganenko et al., 2003; Tsyganenko and Sitnov, 2005, referred

henceforth as T95, T96, T02a, T02b, TSK03, and TS05, respectively) the tail field was represented by a linear combination of two or three partial fields, or "modules" $\mathbf{B}_{T,i}$ (i = 1, 2, 3), corresponding to contributions from disklike current sheets with largely different spatial scales. Each partial field was separately confined inside a model magnetopause by adding to the field of the current sheet a curl-free "shielding" field, which eliminated the normal component of the total field on the magnetopause. As explained in more detail by Sotirelis et al. (1994), this procedure is equivalent to diverting and closing the originally unbounded currents over the magnetopause. Being relatively simple and straightforward, the approach was at the same time inherently limited. First, using the axisymmetric disks excludes at the outset any dawn-dusk asymmetry of the tail current. Even though the observed midtail field was found basically symmetric with respect to the midnight plane (e.g., Fairfield, 1986), one cannot rule out asymmetries at closer distances, especially in the inner tail and near the dawn-dusk flanks of the magnetosphere, in view of significant asymmetries in the measured particle fluxes (e.g., Stubbs et al., 2001). Second, at radial distances larger than $r \sim 5r_{\rm E}$ the equatorial current becomes significantly asymmetric between noon and midnight: on the nightside the current is rather strong and concentrates within a relatively thin sheet, while on the dayside it is much weaker and more spread out in latitude. In the above cited models that kind of asymmetry was taken into account by introducing a variable thickness of the current sheet as a function of X and by requiring that the current had a steep inner edge at $r \sim 10r_{\rm E}$, with virtually no current at smaller distances. In the T02 and TS05 models, the equatorial currents were also allowed to shift along the x-axis within a limited range, in response to varying degrees of disturbance. That added some more flexibility, but the overall geometry of the tail current remained rigidly prescribed by the above a priori assumptions.

The goal of Tsyganenko and Sitnov's (2007) work is to lift most of the limitations of the previous models by using a completely different approach. Instead of approximating the tail field by a few custom-made modules, Tsyganenko and Sitnov (2007) represent it by a series of orthogonal basis functions, each one shielded within a common model magnetopause. As shown below, simply by adding more terms in the expansion, one can set the model's resolution at any desired level (of course, commensurate with the available data coverage). The model easily takes into account the dawn–dusk and noon–midnight asymmetries of the tail currents and couples them with the three-dimensional system of FAC. Moreover, the new method makes it possible to naturally include in the model the fields of the inner magnetospheric sources, such as the SRCs and PRCs. This eliminates the need for sophisticated ad hoc approximations for those fields (Tsyganenko, 2000a) used in T02, TSK03, and TS05 models, and makes empirical approach more consistent.

Tsyganenko and Sitnov (2007) consider a planar current sheet in a cylindrical coordinate system $\{\rho, \phi, z\}$ with the *z*-axis normal to the equatorial plane. The basic idea is to obtain general solutions of the Ampere's equation

$$\nabla \times \mathbf{B} = (4\pi/c) \left[j_{\rho} \left(\rho, \phi \right) \mathbf{e}_{\rho} + j_{\phi} \left(\rho, \phi \right) \mathbf{e}_{\phi} \right] \delta(z)$$
(7.22)

above and below the plane z = 0 and use them for matching the magnetic field of an arbitrary distribution of the equatorial current. One might seek a direct solution of Eq. 7.22 from the very beginning in terms of a vector potential $\mathbf{A}(\rho, \phi, z)$. Unfortunately, that can only be realized for axisymmetric configurations with a purely azimuthal current $j = j(\rho)\delta(z)e_{\phi}$. In that case the vector potential can also be assumed to be purely azimuthal, $\mathbf{A} = A(\rho, z)e_{\phi}$., and resultant scalar equation for $A(\rho, z)$ can be solved by separating variables (Tsyganenko, 1989; Tsyganenko and Peredo, 1994; see also above, Section 7.1). As shown below, derivation of the vector potential in the general case is more involved; yet it is very important, because it will enable further generalization of the model, taking into account the finite thickness of the current sheet and its variation across the tail.

Tsyganenko and Sitnov (2007) obtain the desired solution in three steps. First, Ampere's Eq. 7.22 is reduced to Laplace's equation for scalar potentials γ^+ and $\gamma^$ above and below the equatorial plane, determining there the curl-free magnetic field $B = -\nabla \gamma^{\pm}$. Then the corresponding vector potential is derived from the scalar one, using a transformation by Stern (1987). Finally, the obtained solution is modified, so that the originally infinitely thin current sheet spreads out in the Z direction over a finite thickness. The obtained magnetic field corresponds to an equatorial distribution of the current, infinitely extended in the X and Y directions, while in actuality those currents are spatially bounded, and the corresponding magnetic field is also confined within the magnetopause. As in the earlier models, Tsyganenko and Sitnov (2007) take this into account by adding a curl-free shielding field, whose configuration is determined to minimize the RMS normal component $\langle B_n^2 \rangle^{1/2}$ of the total field at the boundary. One more modification is then carried out, to include in the model the deformation of the tail current sheet due to seasonal and diurnal changes in the orientation of the earth's dipole axis, as well as its twisting during intervals with large azimuthal component of the IMF.

7.2.3 Derivation of Vector Potentials

According to Tsyganenko and Sitnov (2007), for any distribution of currents in the equatorial plane, the magnetic field B outside that plane is both curl-free and divergenceless and, hence, can be represented by the gradient of a scalar potential γ , satisfying Laplace's equation. The potentials γ^+ and γ^- , corresponding to the northern $(0 < z < +\infty)$ and southern $(-\infty < z < 0)$ halfspace, respectively, can be represented by a spectrum of cylindrical harmonics $\gamma_m^{\pm}(k, \rho, \phi, z)$, so that

$$\gamma^{\pm}(\boldsymbol{\rho},\boldsymbol{\phi},z) = \sum_{m=0}^{\infty} \int_{0}^{\infty} \mathrm{d}k a_{m}(k) \gamma_{m}^{\pm}(k,\boldsymbol{\rho},\boldsymbol{\phi},z), \qquad (7.23)$$

where $a_m(k)$ is a set of amplitude functions with the discrete azimuthal and continuous radial wave numbers *m* and *k*, respectively, and (e.g., Moon and Spencer, M1971)

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$$\gamma_m^{\pm}(k,\rho,\phi,z) = \pm J_m(k\rho) \left\{ \begin{array}{l} \sin\left(m\phi\right)\\ \cos\left(m\phi\right) \end{array} \right\} \exp\left(-k|z|\right) \tag{7.24}$$

in which J_m are Bessel functions of the *m*th order. The sign factor in Eq. 7.24 ensures the continuity of the normal magnetic field component B_z across the plane z = 0, required by $\nabla \cdot \mathbf{B} = 0$. The tangential component of the magnetic field has a jump ΔB_t across the equatorial plane, related to the corresponding surface density J of the equatorial current by $J = (c/4p)(e_z \times \Delta B_t)$. According to Stern (1987), in cylindrical coordinates the transition from scalar to vector potentials can be done using the transformation

$$\mathbf{A} = \boldsymbol{\rho}^2 \nabla \Psi \times \nabla \boldsymbol{\phi}, \tag{7.25}$$

where the generating function Ψ is related to the scalar potential γ by the equation

$$\gamma = -\partial \Psi / \partial \phi. \tag{7.26}$$

A generating function Ψ_m satisfying Eqs. 7.24 and 7.26 can be taken in the form

$$\Psi_m^{\pm} = \pm \frac{J_m(k\rho)}{m} \left\{ \frac{\sin(m\phi)}{\cos(m\phi)} \right\} \exp\left(-k|z|\right).$$
(7.27)

Then the corresponding vector potential reads

$$\mathbf{A}_{m}^{(k,\rho,\phi,z)} = -\frac{k\rho}{m} \left[J_{m}(k\rho) \,\mathbf{e}_{\rho} + \operatorname{sign}(z) J_{m}'(k\rho) \,\mathbf{e}_{z} \right] \left\{ \begin{array}{c} \sin\left(m\phi\right) \\ \cos\left(m\phi\right) \end{array} \right\} \exp\left(-k\left|z\right|\right).$$
(7.28)

Tsyganenko and Sitnov (2007) noted that the above derivation of the vector potential is valid only for the case of axially asymmetric fields with m = 1, 2, ... The axisymmetric case m = 0 must be treated separately, and there exist two seemingly equivalent solutions. The first one can be derived using the same procedure: start from the scalar potential

$$\gamma_0^{\pm} = \pm J_0(k\rho) \exp(-k|z|)$$
 (7.28a)

and obtain a generating function (in this case, just by multiplying γ_0^{\pm} by $-\phi$), which yields the vector potential as

$$\mathbf{A}_{0}(k,\rho,\phi,z) = -k\phi\rho\exp\left(-k|z|\right)\left[J_{0}\left(k\rho\right)\mathbf{e}_{\rho} + \operatorname{sign}\left(z\right)J_{0}'\left(k\rho\right)\mathbf{e}_{z}\right].$$
(7.29)

The second solution is a purely azimuthal vector potential, derived in Tsyganenko (1989) and Tsyganenko and Peredo (1994):

$$\mathbf{A}_{0}\left(k,\boldsymbol{\rho},z\right) = J_{1}\left(k\boldsymbol{\rho}\right)\exp\left(-k\left|z\right|\right)\mathbf{e}_{\phi}.$$
(7.30)

By taking curls of Eqs. 7.29 and 7.30 one can verify that these two potentials are equivalent, that is, they yield identical magnetic fields. This equivalence extends to a more general case of a current sheet with a finite (but constant) thickness, but it fails as we further generalize the solution by allowing the thickness to vary with

X and Y (more details below). In that case, the components of B generated by the potential Eq. 7.29 acquire terms proportional to the azimuthal angle and, hence, become nonperiodical functions of ϕ , which is unacceptable. The second solution Eq. 7.30 remains well behaved in that sense and, hence, it was chosen to represent the axisymmetric part of the model field.

Then Tsyganenko and Sitnov (2007) generalize the obtained vector potentials by taking into account the finite thickness of the current sheet. This is easily achieved by the following replacing

$$|z| \rightarrow \zeta = \sqrt{z^2 + D^2}, \operatorname{sign}(z) \rightarrow z/\zeta,$$
 (7.30a)

which broadens the initially delta-like profile of the current density. Moreover, the half-thickness scale *D* can be allowed to vary across the tail, $D = D(\rho, \phi)$. With these modifications, the vector potentials take the form

$$\mathbf{A}_0(k,\boldsymbol{\rho},z) = J_1(k\boldsymbol{\rho})\exp\left(-k\boldsymbol{\zeta}\right)\mathbf{e}_{\boldsymbol{\phi}},\tag{7.31}$$

$$\mathbf{A}_{m}^{(k,\rho,\phi,z)} = -\frac{k\rho}{m} \left[J_{m}(k\rho) \,\mathbf{e}_{\rho} + \frac{z}{\zeta} J_{m}'(k\rho) \,\mathbf{e}_{z} \right] \left\{ \begin{array}{c} \sin\left(m\phi\right) \\ \cos\left(m\phi\right) \end{array} \right\} \exp\left(-k\zeta\right). \tag{7.32}$$

Returning to the general expansion for an arbitrary distribution of the equatorial current, Tsyganenko and Sitnov (2007) replaced Eq. 7.23 with

$$\mathbf{A}\left(\boldsymbol{\rho},\boldsymbol{\phi},z\right) = \sum_{m=0}^{\infty} \int_{0}^{\infty} \mathrm{d}k a_{m}\left(k\right) \mathbf{A}_{m\left(k,\boldsymbol{\rho},\boldsymbol{\phi},z\right)},\tag{7.33}$$

where the "partial" vector potentials A_m are given by Eqs. 7.31 and 7.32.

Tsyganenko and Sitnov (2007) noted that a novel feature of their work is that they expand the tail field model beyond the first term in Eq. 7.33 with m = 0, that is, they introduce a plethora of azimuthally asymmetric elementary current sheets with $m \neq 0$. This makes it possible to approximate with any desired resolution the magnetic field due to any distribution of the equatorial current. In this regard, they note that all the earlier models (Tsyganenko, 1989; Tsyganenko, 1996; Tsyganenko, 2002; Tsyganenko and Sitnov, 2005) used special forms of the amplitude function $a_0(k)$, which yielded smooth radial distributions of the magnetotail current J(r), with a single peak at $r \sim 10r_E$ and a gradual tailward decrease beyond that distance. This approach resulted in computationally simple codes; however, it also restricted the models' scope to a limited class of a priori prescribed distributions of the tail field. Therefore, Tsyganenko and Sitnov (2007) abandon most of the previous ad hoc assumptions and leave it entirely to the model and data to establish the actual structure of the magnetic field. To that end, Tsyganenko and Sitnov (2007) replace in Eq. 7.33 the integration over a continuous spectrum $a_m(k)$ by a discrete summation over an equidistant set of wave numbers k_n :

$$\mathbf{A}(\rho,\phi,z) = \sum_{n=1}^{N} a_{0n} \mathbf{A}_{o}(k_{n},\rho,z) + \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn} \mathbf{A}_{m}(k_{n},\rho,\phi,z),$$
(7.34)

where the axisymmetric part of the vector potential is singled out into a separate sum, and

$$k_n = n/\rho_0, \tag{7.34a}$$

where ρ_0 is a radial scale, corresponding to the largest wavelength in the expansion of the potential into the series of finite elements. By the order of magnitude, its value should correspond to the spatial extent of the modeling region; in Tsyganenko and Sitnov (2007) it was choused $\rho_0 = 20 r_E$. The upper limits of the summation, N and M, define the radial and the angular (azimuthal) resolution of the model, respectively. Their optimal choice translates into a trade-off between the computational efficiency of the model and the available degree of details, which critically depends on the coverage of the modeled region by the data.

7.2.4 Magnetic Field Components

According to Tsyganenko and Sitnov (2007), the expansion described by Eq. 7.34 for the vector potential generates a corresponding expansion for the magnetic field vector, in which the first (axisymmetric) sum will be designated by the superscript *s* (standing for "symmetric"). The second sum will be further divided into two parts. The first part corresponds to choosing the factor $\sin(m\phi)$ in the right-hand side of Eq. 7.32, and it will be called the "odd" mode (designated by the superscript *o*), since in this case both components of A are odd functions of the coordinate *y*. The second part will be termed the "even" mode (hence, *e*). With all these notations, it will now be

$$\mathbf{B}(\rho,\phi,z) = \sum_{n=1}^{N} a_n^{(s)} \mathbf{B}_n^{(s)} + \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn}^{(o)} \mathbf{B}_{mn}^{(o)} + \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn}^{(e)} \mathbf{B}_{mn}^{(e)},$$
(7.35)

where

$$B_{n,\rho}^{(s)} = k_n J_1(k_n \rho) \left(\frac{z}{\zeta}\right) \exp\left(-k_n \zeta\right); \ B_{n,\phi}^{(s)} = 0;$$

$$B_{n,z}^{(s)} = k_n \exp\left(-k_n \zeta\right) \left[J_0(k_n \rho) - \frac{D}{\zeta} \frac{\partial D}{\partial \rho} J_1(k_n \rho)\right],$$
(7.36)

$$B_{mn,\rho}^{(o)} = -\frac{k_n z}{\zeta} J_m'(k_n \rho) \exp\left(-k_n \zeta\right) \left[\cos\left(m\phi\right) - \frac{D}{m\zeta} \frac{\partial D}{\partial \phi} \left(k_n + \frac{1}{\zeta}\right) \sin\left(m\phi\right) \right];$$

$$B_{mn,\phi}^{(o)} = \frac{k_n z}{\zeta} J_m'(k_n \rho) \exp\left(-k_n \zeta\right) \left[\frac{m}{k_n \rho} J_m(k_n \rho) - \frac{\rho D}{m\zeta} \frac{\partial D}{\partial \rho} \left(k_n + \frac{1}{\zeta}\right) J_m'(k_n \rho) \right] \sin\left(m\phi\right);$$

$$B_{mn,z}^{(o)} = k_n J_m(k_n \rho) \exp\left(-k_n \zeta\right) \left[\cos\left(m\phi\right) - \frac{k_n D}{m\zeta} \frac{\partial D}{\partial \phi} \sin\left(m\phi\right) \right],$$
(7.37)

$$B_{mn,\rho}^{(e)} = -\frac{k_n z}{\zeta} J_m'(k_n \rho) \exp\left(-k_n \zeta\right) \left[\sin\left(m\phi\right) + \frac{D}{m\zeta} \frac{\partial D}{\partial \phi} \left(k_n + \frac{1}{\zeta}\right) \cos\left(m\phi\right) \right];$$

$$B_{mn,\phi}^{(e)} = -\frac{k_n z}{\zeta} \exp\left(-k_n \zeta\right) \left[\frac{m}{k_n \rho} J_m(k_n \rho) - \frac{\rho D}{m\zeta} \frac{\partial D}{\partial \rho} \left(k_n + \frac{1}{\zeta}\right) J_m'(k_n \rho) \right] \cos\left(m\phi\right);$$

$$B_{mn,z}^{(e)} = k_n J_m(k_n \rho) \exp\left(-k_n \zeta\right) \left[\sin\left(m\phi\right) + \frac{k_n D}{m\zeta} \frac{\partial D}{\partial \phi} \cos\left(m\phi\right) \right],$$
(7.38)

Equations for the corresponding components B_{ρ} , B_{ϕ} , and B_z of the magnetic field include spatial derivatives of the half-thickness $D(\rho, \phi)$ of the current sheet. The structure of the model field can be better visualized by plotting families of flow lines of the corresponding electric current $\mathbf{j} = \nabla \times \mathbf{B}$, for various values of wave numbers k_n and azimuthal harmonic orders *m*. Figure 7.13 displays four sample plots, from a large-scale symmetric current disk (m = 0, k = 0.1, top, left) to a higher-order (m = 2), smaller-scale (k = 0.3) element with an *o*-type symmetry (bottom, right).

The plots in Fig. 7.13 were obtained assuming a constant thickness of the current sheet $D = 2r_E$. Using a linear combination of a sufficiently large number of such elements allows one to approximate the magnetic field for any distribution of the equatorial current.



Fig. 7.13 Sample configurations of the equatorial electric current flow lines, corresponding to four harmonics of the vector potential Eqs. 7.31 and 7.32 (From Tsyganenko and Sitnov, 2007)

7.2.5 Spatial Variation of the Current Sheet Thickness

Tsyganenko and Sitnov (2007) noted that assuming a constant half-thickness D of the equatorial current sheet is only a crude approximation. In the distant tail, the plasma sheet is quite variable and turbulent, so that the local current sheet thickness can vary within a wide range, resulting in larger values of D. At closer distances, owing to the rapidly increasing dipole field one may expect a more regular structure of the equatorial current, concentrated within a limited range of latitudes around the dipole equator, where the magnetic field magnitude is minimal. Therefore, in the inner magnetosphere the current sheet thickness on the order of magnitude, does not exceed a fraction of the corresponding L-parameter and, hence, should decrease with decreasing geocentric distance. On the other hand, as was found in all previous empirical modeling studies (Tsyganenko, 1987 and later models), the tail current sheet expands in the Y-direction toward its dawn–dusk flanks. Finally, due to a generally compressed magnetic field on the dayside, equatorial currents in that region are expected to spread over a larger interval of latitudes than on the nightside, implying larger values of D there.

According to Tsyganenko and Sitnov (2007), the above features can be taken into account by a straightforward modification of the model, in which the parameter D is assumed as a simple analytical function of position on the equatorial plane. They chose it in the following form:

$$D = D_0 \left[1 - f(\varepsilon) \frac{\rho_D^2}{\rho_D^2 + \rho^2} \right] \left[1 + \alpha \exp(X/10) \right] \exp[\beta(Y/20)], \quad (7.39)$$

where D_0 is the asymptotic half-thickness of the current sheet in the center of the distant tail, f is the magnitude of the sheet thinning in the inner magnetosphere, $\rho_D = 5 r_E$, and the coefficients α and β define the rate of the current sheet expansion in the sunward and dawn–dusk directions, respectively. To avoid negative values of D, the coefficient f was intentionally taken in the form

$$f(\varepsilon) = 0.5(1 + \tanh(\varepsilon)), \tag{7.39a}$$

so that $|f(\varepsilon)| < 1$ for any value of the variable parameter ε . In total, the form Eq. 7.39 includes four variable parameters.

7.2.6 Approximations for the Shielding Field

Tsyganenko and Sitnov (2007) noted that as in the earlier works (Tsyganenko, 1996, and more recent models), their approach is to define and add a corresponding shielding field \mathbf{B}_{sh} to each of the individual modules $\mathbf{B}_n^{(s)}$, $\mathbf{B}_{mn}^{(o)}$, and $\mathbf{B}_{mn}^{(e)}$ in Eq. 7.35, so that the final expansion for the total field of equatorial currents becomes

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$$\mathbf{B}_{eq} = \sum_{n=1}^{N} a_n^{(s)} \left(\mathbf{B}_n^{(s)} + \mathbf{B}_{\text{sh},n}^{(s)} \right) + \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn}^{(o)} \left(\mathbf{B}_{mn}^{(o)} + \mathbf{B}_{\text{sh},mn}^{(o)} \right) + \sum_{m=1}^{M} \sum_{n=1}^{N} a_{mn}^{(e)} \left(\mathbf{B}_{mn}^{(e)} + \mathbf{B}_{\text{sh},mn}^{(e)} \right)$$
(7.40)

This ensures a full confinement of the total field inside the magnetopause, regardless of specific values of the amplitude coefficients $a_n^{(s)}$, $a_{mn}^{(o)}$, and $a_{mn}^{(e)}$ in the expansion. A great advantage of this approach is that it allows defining $\mathbf{B}_{sh,n}^{(s)}$, $\mathbf{B}_{sh,mn}^{(o)}$, and $\mathbf{B}_{sh,mn}^{(e)}$ only once, after which the model can be fitted to any set of data by varying the coefficients, but without recalculating the shielding fields. Since the shielding currents flow at the magnetopause, their field inside the magnetosphere can be described using a scalar potential. In particular, the shielding fields $\mathbf{B}_{sh}^{(s)}$, $\mathbf{B}_{sh}^{(o)}$, and $\mathbf{B}_{sh}^{(e)}$ for each term in Eq. 7.40 can be constructed using expansions in cylindrical harmonics similar to Eq. 7.24:

$$U = \sum_{k=1}^{K} \sum_{l=0}^{L} c_{kl} J_l(k_k \rho) \left\{ \frac{\cos\left(l\phi\right)}{\sin\left(l\phi\right)} \right\} \sinh\left(k_k z\right),\tag{7.41}$$

where the factor $\cos(l\phi)$ corresponds to the terms having the *s*-symmetry and *o* symmetry, and $\sin(l\phi)$ enters in the *e*-terms. The summation limits *K* and *L* were chosen equal to 5 and 15, respectively, to provide a reasonable trade-off between the relative RMS error (on the order of 7–10%) and the length of expansions (hence, computation time). Expansions for individual magnetic field components can be obtained by taking the gradient of Eq. 7.41 and are similar in their structure to Eqs. 7.36, 7.37, and 7.38. Figure A7.1 illustrates the effect of the shielding by showing sample distributions of the normal component B_n of the unshielded field on the model magnetopause (left panel), taken with the opposite sign, and the corresponding normal component $B_{sh,n}$ of the shielding field (right panel) for the term with m = 4 and n = 3 in the second double sum in Eq. 7.39.

As mentioned Tsyganenko and Sitnov (2007), in an ideal case of a perfect shielding, $B_n + B_{sh,n} = 0$, and the two distributions would be identical. Using the finite expansion described by Eq. 7.40, however, limits the accuracy and, even though the overall agreement is satisfactory, both negative (red) and positive (blue) peaks of $B_{sh,n}$ are located somewhat farther from the equatorial plane than those in the unshielded field distribution. This discrepancy can be reduced by adding more terms in the expansion described by Eq. 7.40, and thus increasing its flexibility near the flanks of the current sheet, where the magnetic field rapidly reverses its orientation across the equatorial plane.

7.2.7 Contribution from Field-Aligned Currents

In Tsyganenko and Sitnov (2007) modeling of the field B_{FAC} of field-aligned currents (FACs) essentially relies on the approach developed earlier in Tsyganenko

(2002a). Both Region 1 and Region 2 FACs were assumed to flow into and out of the ionosphere along closed contours encircling the polar cap, so that in each case the current flow lines are confined to analytically defined surfaces, S_1 or S_2 , respectively. At low altitudes, the shape of each surface approximately matches the diverging dipolar field lines, but then gradually stretches out at larger radial distances. The strength of the upward-downward currents was defined as a simple sinusoidal function of the foot point solar-magnetic longitude ϕ . For each current system, the corresponding magnetic field B_{FAC} was first calculated numerically at a grid of points covering a wide range of distances, by means of a Biot-Savart integration. The next step was to derive a suitable analytical model, yielding the best fit to the numerically obtained set of field vectors. As a convenient zero-order approximation $\mathbf{B}_{FAC}^{(o)}$ Tsyganenko and Sitnov (2007) chose the "conical" harmonics (Tsyganenko, 1991), corresponding to purely radial currents that flow within a conical sheet $S_{\rm c}$ of finite thickness, with the current density varying with the longitude as $sin(m\phi)$ (m = 1, 2, ...). These harmonics will be called "antisymmetric," because in this case the FACs at dawn and dusk have the same magnitude but opposite directions, e.g., downward at dawn and upward at dusk. Since the shape of the conical current sheets grossly differs from that of the surfaces S_1 and S_2 , the corresponding zero-order magnetic field $\mathbf{B}_{FAC}^{(o)}$ is also different from the numerically computed B_{FAC} . To bring them into closer agreement, the zero-order field $B_{FAC}^{(o)}$ was modified by applying a flexible deformation of space in spherical coordinates $R \Rightarrow R^*$. The deformation parameters were found by minimizing the RMS difference between the numerically computed field B_{FAC} and its analytical approximation $\mathbf{B}_{FAC}^{(o)}$, obtained by deforming the conical field as

$$\mathbf{B}_{\rm FAC}' = \mathbf{\hat{T}} \mathbf{B}_{\rm FAC}^{(o)}(\mathbf{R}^*),\tag{7.42}$$

where $\hat{\mathbf{T}}$ is the deformation tensor (Tsyganenko, 1998). The best-fit deformation yielded the desired analytical approximation for the field B_{FAC} and transformed the original conical current sheet S_c into a modified surface, close to that used in the numerical computation (i.e., either S_1 or S_2). As was already discussed in Tsyganenko (2002a, b), the Region 2 currents and the PRC should be viewed as a single-current system because they are driven by the same physical mechanism (that is, sunward plasma convection in the inner tail) and are located in the same region. In the Tsyganenko (2002a, b) model, however, for the sake of mathematical tractability they were treated as separate sources, so that the model PRC represented the innermost part of the system confined within $r \sim 5 r_E$, while the model Region 2 currents extended to larger distances and blended there with the cross-tail current. That artificial separation was dictated by an inherent deficiency of the model of deformed conical currents, namely, by the lack of the azimuthal component of j, needed to close them in the plasma sheet. The described approach offers a natural way to include the closure currents at low latitudes, and thus eliminates the need in a separate PRC module. Figure 7.14 qualitatively explains the idea: its essence is to divert in the azimuthal direction the radial component of the model FAC in the plasma sheet, merely by adding a suitable distribution of equatorial currents.

 $\langle \rangle$



Fig. 7.14 Schematic illustration of the Region 2 FAC and PRC current systems, obtained by combining the deformed conical model of Tsyganenko (2002a, b) with the flexible equatorial currents, corresponding to Eq. 7.35. *Top*: the conical Tsyganenko (2002a, b) FACs (*left*) are diverted by adding a system of equatorial currents (*center*), which results in a two-loop ("quadrupole") three-dimensional current system, localized at closer geocentric distances (*right*). Bottom: adding an axisymmetric ring current (*center*) to the above system converts it into a PRC, peaked in the evening sector (*right*) (From Tsyganenko and Sitnov, 2007)

As a first step (Fig. 7.14, top), Tsyganenko and Sitnov (2007) add a distribution with oppositely directed radial currents, which cancels the original currents at large distances and thus confines them to the inner magnetosphere as a twoloop three-dimensional system, termed in an earlier work as a "quadrupole" current (Tsyganenko, 2000a). Adding then a suitably distributed axisymmetric ring current (Fig. 7.14, bottom) weakens the eastward current on the morning side, but strengthens the westward current in the evening sector, which results in a typical PRC configuration.

Tsyganenko and Sitnov (2007) note that the above scheme just illustrates the principle: in fact, there is no need to add any more special terms into the model, because the expansion described by Eq. 7.35 for the field of equatorial currents, due to its great flexibility will automatically include the effect of the closure currents for the FAC system, merely by a proper adjustment of its coefficients. Also, they note that the model allows to easily reproduce the dawn–dusk asymmetry of the FAC/PRC system, an inherent feature of the storm-time magnetosphere. To that end, they in-troduce a "symmetric" component in the FAC system, in which the downward currents are localized around noon and upward currents near midnight. Although such a possibility was briefly discussed in Tsyganenko (2000a), the symmetric FAC was not included in the Tsyganenko (2000a, b) model; instead, the PRC was allowed to rotate around the solar-magnetic *z*-axis and thus replicate the duskside storm-time depression of the geomagnetic field. In the described model Tsyganenko and Sitnov (2007) do not have a separate PRC module, and the westward rotation of the Region 2 FAC (shown in Fig. 7.14) is taken into account by adding a symmetric Fourier mode of the FAC, similar to the antisymmetric one with m = 1, but with the corresponding current varying with longitude as $\cos \phi$ instead of $\sin \phi$. Tsyganenko and Sitnov (2007) note that this mode of FAC has the same type of dawn–dusk symmetry/antisymmetry as the "e-modes" of the field from the equatorial currents given by Eq. 7.38. Similarly to all other magnetospheric field sources, the field $\mathbf{B}_{FAC}^{(o)}$ should also be confined within the magnetopause and, hence, must be complemented by a corresponding shielding field. As in Tsyganenko (2000a), Tsyganenko and Sitnov (2007) represented that field by a set of box harmonics having a generic form

$$u_{ik} \approx \exp\left[x\left(p_i^{-2} + q_k^{-2}\right)\right] \left\{ \begin{array}{c} \cos\left(y/p_i\right) \\ \sin\left(y/p_i\right) \end{array} \right\} \left\{ \begin{array}{c} \cos\left(z/q_k\right) \\ \sin\left(z/q_k\right) \end{array} \right\}$$
(7.43)

These harmonics were used for the shielding of both antisymmetric and symmetric terms in the FAC field, with the choice between sin and cos based in each case on the required parity of the magnetic field components.

7.2.8 Data Used for Magnetosphere Modeling

As mentioned above, a principal goal of Tsyganenko and Sitnov (2007) work was to develop a modeling tool, capable of deriving from the data as much as possible information on the large-scale magnetospheric structure. The size of the database is a critical factor in such studies, so every effort was made to maximize the amount of available data by including observations from new missions and expanding the previously existing sets.

Geotail data. The 13-year set of Geotail magnetometer data used in Tsyganenko and Sitnov (2007) study included more than 10 years of observations in the near-tail at $10r_E \le r \le 30r_E$. Owing to the low inclination of Geotail, it provided a perfect coverage of the plasma sheet and adjacent tail lobe area. A comprehensive overview of the spacecraft orbit and the instrument can be found elsewhere (Nishida, 1994; Kokubun et al., 1994). The original data with 1-min resolution were first filtered to remove bad records and then corrected for a systematic offset in the B_z component, using high-resolution 3-s data from Geotail solar-wind intervals and a variant of the Davis–Smith method (Davis and Smith, 1968; Belcher, 1973). The corrected data were averaged over 5-min intervals and subjected to a visual screen-by-screen inspection to remove the data taken outside the magnetosphere, identified with the help of concurrent key parameter plasma data.

Cluster data. A new resource of magnetometer data, not yet tapped in previous modeling studies, was the Cluster data archive at NSSDC CDAWEB. The original data also came with 1-min resolution and were processed using basically the same procedures as for Geotail. In order to more accurately identify the magnetopause crossings, Tsyganenko and Sitnov (2007) used the data on the proton bulk flow speed obtained by the Cluster Ion Spectrometer (Reme et al., 2001), available

from the same online source. The data spanned the period from February 2001 to July 2005 and included in total 65,755, 15-min averages, spatially distributed at significantly higher latitudes than the Geotail data and covering the range of radial distances between 4 and $19r_E$. More details on the orbital design of the Cluster mission and its magnetic field experiment can be found elsewhere (Escoubet et al., 2001; Balogh et al., 2001).

Polar data. The Polar magnetic field experiment (Russell et al., 1995) was initially conceived for studying the high-latitude magnetosphere up to geocentric distances of $9r_{\rm E}$. Owing to the extended lifetime of the experiment and to the slow rotation of Polar's line of apsides, the spacecraft provided complete coverage of the entire inner magnetosphere during more than 10 years of its operation. The Polar data were prepared from 55-s averages downloaded from UCLA Polar website and covered the period from the launch (March 1996) through September 2005. All the data were visually inspected to eliminate bad records and magnetosheath/solar wind intervals, and then divided into two subsets, corresponding to high-altitude $(5.0 \le r \le 9.0 r_F)$ and low-altitude $(3.2 \le r \le 5.0 r_F)$ ranges of the geocentric distance. The data in the high-altitude subset were then averaged over 15-min intervals, while for the low-altitude subset Tsyganenko and Sitnov (2007) chose a shorter averaging interval of only 5 min, taking into account the much higher speed of the spacecraft near earth. Retaining the 15-min averaging in that region would result in too long orbital segments and, hence, would smear out the spatial structure of the field in the innermost magnetosphere. In total, Polar data included 212,891 data records from the high-altitude region (15-min averages) and 103,856 records from the low-altitude region (5-min averages). In terms of the number of data points, Polar contributed nearly 27% of the total in the entire database.

Geosynchronous data. Magnetic field data from synchronous orbit is a valuable resource for the magnetospheric modeling. During the last decade, most of the contribution to the synchronous data pool came from four satellites, GOES-8, GOES-9, GOES-10, and GOES-12 that provided almost continuous simultaneous monitoring of the magnetic field at two geographic longitudes, about 5 h apart in local time. The synchronous orbit is important not only from a practical viewpoint, but also due to its unique location as a dividing line between the stable, mostly quasi-dipolar inner geomagnetic field, and much more variable outer field, often becoming tail-like during disturbed times. The synchronous data were processed in Tsyganenko and Sitnov (2007) using basically the same procedures as the data of other spacecrafts. In contrast to purely scientific missions, the GOES satellites are not magnetically clean, and in some instances, the original data were found to be contaminated by onboard sources of magnetic field. For that reason, special attention was given to visual identification and filtering out of bad data intervals, along with the magnetosheath intervals during strong compressions of the magnetopause, when the dayside boundary crossed the synchronous orbit. In total, the data of four GOES spacecraft contributed 625,481 data records with 15-min average values of the magnetic field, constituting about 54% of the total number of records in the modeling data sets.

IMP-8 data. As noted Tsyganenko and Sitnov (2007), IMP-8 spacecraft became famous for its outstanding longevity among other space physics missions (launched in 1973, retired in 2001). Owing to its orbital parameters (a quasi-circular orbit with $r \sim 30-40 r_{\rm E}$), IMP-8 served for many years as a unique source of solar-wind and IMF data, though it also contributed to several statistical studies of the magnetotail structure (e.g., Kaymaz et al., 1994). Tsyganenko and Sitnov (2007) included in their database magnetospheric magnetic field data of IMP-8 taken during 1995–2000, when concurrent solar-wind data from WIND and ACE became available. Because of a long orbital period (12.5 days) and a limited magnetospheric residence time, the number of IMP-8 data records in their database is comparatively small, only 16,317 records, that is, 1.4% of the total. Nonetheless, Tsyganenko and Sitnov (2007) consider them as an important addition to the data set, since they cover a severely underrepresented region of the distant tail ($r \sim 30-40 r_{\rm E}$) with much fewer Geotail observations.

Solar wind and IMF data. In the recent studies of Tsyganenko (2002a, b), Tsyganenko et al. (2003) and Tsyganenko and Sitnov (2005), dedicated sets of the solar-wind and IMF data with 5-min resolution, prepared from wind, ACE, and IMP-8 observations were used. Tsyganenko and Sitnov (2007), in contrast, used hourly averages from OMNI database (ftp://nssdcftp.gsfc.nasa.gov/spacecraft_ data/omni/), for the following reasons. First, given the large separation between the solar-wind monitors and earth (in both the sun-earth and transverse directions), using the data with 5-min resolution is not always warranted because of inevitable accumulation of large errors in the calculated propagation times between the spacecraft and the magnetosphere and additional inaccuracies, associated with lack of information on the orientation of discontinuities in the solar wind. Second, the solarwind data, especially the proton density, taken simultaneously but at different locations by different spacecraft, can differ significantly. This can even be the case for different instruments on the same spacecraft, or different methods of data processing (i.e., moments versus nonlinear analysis of distribution functions). This calls for adopting a single standard interplanetary medium data set for space weather studies, especially in the development of quantitative magnetospheric models. The OMNI data can be viewed as a good candidate for such a standard, all the more so when a high-resolution version of the OMNI data resource is currently under construction (King and Papitashvili, 2005). Finally, Tsyganenko and Sitnov (2007) focused mostly on average structures of the magnetosphere, corresponding to a set of fixed bins of interplanetary parameters and, hence, there is no need to know in great detail the dynamics of the incoming solar wind.

7.2.9 Regularization of Matrix Inversion Procedures

As underlined by Tsyganenko and Sitnov (2007), a distinctive feature of the new approach is the large number of elementary magnetic field sources, whose amplitudes need to be found by fitting the Eq. 7.40 to data. The specific models have

about a hundred elements describing the field of equatorial currents, each of which is shielded using a comparable number of the magnetopause field elements. All the shielding coefficients are determined prior to the main procedure of fitting the model to spacecraft data and, once found, need not to be changed. In that sense, the shielding procedure is uncoupled from the main fitting and, hence, does not significantly strain the computer resources. Yet, already at the shielding stage, the use of the Gauss method of matrix inversion, employed in the earlier models, was found to result in serious problems: the range of best-fit values of the shielding coefficients quickly expanded with the increase in their number, and the effect was further amplified when fitting the model to spacecraft data. To regularize the procedure and achieve a trade-off between the accuracy of the fitting and the noise in the best-fit coefficients, Tsyganenko and Sitnov (2007) employed a new technique, based on the singular value decomposition (SVD) method (Press et al., M1992). The central idea of the method is to represent the least-squares normal equation matrix as a product of two orthogonal matrices and one diagonal matrix containing positive numbers, the so-called singular values. Then, in the process of the matrix inversion the smallest singular values are excluded, so that their inverse values are replaced by zeros. The number of singular values to be excluded is controlled by the tolerance parameter, which is usually the ratio between the smallest and the largest singular values to be retained. Tsyganenko and Sitnov (2007) found the SVD approach to be a very powerful tool to effectively regularize all the data-fitting procedures, providing an accurate matrix inversion with reasonable amplitudes of the least-squares coefficients.

7.2.10 Data Weighting

According to Tsyganenko and Sitnov (2007), another problem arising from the increasing amount of data and the higher spatial resolution is a strong non-uniformity of the data coverage due to a limited number of spacecraft and their different orbital parameters. Figure 7.15 shows a histogram of the radial distribution of data in a subset corresponding to quiet conditions with $K_p \leq 1$ (a total of 174,137 averages), binned into $0.5 r_{\rm E}$ intervals of the geocentric distance.

Figure 7.15 shows that even with the logarithmic scale of the vertical axis masking the large variation of the data density, it is evident that the biggest portion of data is confined within $r \leq 10r_{\rm E}$, and there is a strong disparity between the relatively sparse population of Geotail and Cluster data points in the midtail region and much denser coverage of the inner magnetosphere by Polar and GOES, the latter's contribution being confined to a narrow range of GSM latitudes and a single value of the synchronous radial distance, manifested by a sharp peak at $r = 6.6 r_{\rm E}$ in the plot. The secondary peaks correspond to the boundary between the regions with 5- and 15-min averaging of Polar data (at $r \approx 5 r_{\rm E}$) and to the apogees of Polar, Cluster, and Geotail ($r \approx 9r_{\rm E}$, $r \approx 19 r_{\rm E}$, and $r \approx 30 r_E$, respectively), where the spacecraft move most slowly and hence collect the largest amount of data.



Fig. 7.15 Radial distribution of data points in the modeling data set, binned into $0.5 r_E$ intervals of the geocentric distance (solid line). Note the log scale on the vertical axis and a sharp peak at 6.6 r_E due to the GOES data. Local peaks corresponding to apogees of individual spacecraft are also indicated. Applying the weight function, inversely proportional to the radial density of the data, results in a nearly constant normalized data density (dotted line), except in the distant tail beyond 30 r_E . From Tsyganenko and Sitnov (2007)

In more quantitative terms, the interval $3r_E \le r \le 10 r_E$ contains 83.5% of all data points, of which 64.5% belong to the GOES data at $r = 6.6 r_E$. In contrast, the intervals $10r_E \le r \le 20 r_E$, $20 \le r \le 30r_E$, and $30 \le r \le 40 r_E$ yield only 7.7, 5.5, and 3.1% of all data, respectively. Tsyganenko and Sitnov (2007) noted that in this situation, using the unnormalized data in the least-squares fitting might result in a significant bias of the reconstructed field in the underpopulated magnetotail. To avoid that, Tsyganenko and Sitnov (2007) introduced a weighting procedure, in which the weight *W* was calculated as a function of the radial distance *r* in the following way. The entire range of the radial distance containing the data was binned into $0.5 r_E$ intervals, and each bin was assigned a partial weight

$$W_i = \langle \Delta N \rangle / \max\{0.2 \langle \Delta N \rangle, \Delta N_i\}, \qquad (7.44)$$

where ΔN_i are the numbers of data points in the *i*th bin and $\langle \Delta N \rangle$ is the average number per bin over the entire set. To avoid excessively large weights for severely underpopulated bins with too little data points, a lower limit was set on their number, so that if ΔN_i dropped below 20% of the average, the weight W_i was capped from above, not to exceed 5.0. The normalized radial distribution of the data density obtained by multiplying $\Delta N / \Delta r$ by W_i is shown in Fig. 7.15 by a dotted line. The normalization effectively levels the data distribution everywhere, except in the distant tail beyond Geotail's apogee, where it falls off because of too small a number of observations and the capping condition.

7.2.11 Binning by K_p Index

The first set of the least-squares fitting runs was made by Tsyganenko and Sitnov (2007) for a sequence of bins of the geomagnetic activity $K_{\rm D}$ index, as in the old Tsyganenko and Usmanov (1982), Tsyganenko (1987), and Tsyganenko (1989) models. In this case the summation upper limits in Eq. 7.40 were chosen as M = 4and N = 5. It should be noted that Tsyganenko and Sitnov (2007) did not impose any restrictions on the range of the solar-wind dynamic pressure P_{dyn} in the data subsets and, since that parameter is of primary importance in controlling the strength of the global magnetotail magnetic field (e.g., Tsyganenko, 2000b), it had to be somehow included in the model. To that end, Tsyganenko and Sitnov (2007) modified the Eq. 7.40 by representing each of the coefficients $a_n^{(s)}$, $a_{mn}^{(o)}$, and $a_{mn}^{(e)}$, as binomials having the form $a_0 + a_1 \sqrt{P_{dvn}}$. This modification doubled the number of unknown coefficients and thus brought their total number in Eq. 7.40 up to 90. The model FAC contributed four more coefficients, including the first and second antisymmetric Fourier modes for the Region 1 system, as well as antisymmetric and symmetric principal modes for Region 2. Finally, Tsyganenko and Sitnov (2007) also added a term, corresponding to a uniform magnetic field along the z_{GSM} -axis, to take into account the "penetration" (or "interconnection") magnetic field, similar to that entering in the Tsyganenko (1996), Tsyganenko (2002a, b), and Tsyganenko and Sitnov (2005) approximations. In those models, the penetration field was a priori assumed to be proportional and, hence, directly controlled by the perpendicular component of the concurrent IMF. The degree of that control was defined by a proportionality factor derived from the data, and its best-fit value varied between the models from 0.4 to 0.8. Tsyganenko and Sitnov (2007) assumed a simpler version of the interconnection field, derived from a binned data subset just as a vector $\delta B_z \mathbf{e}_z$ in the Z direction. Adding this term to the model resulted in a tangible improvement of the model's figure of merit and, most interesting, revealed a strong and stable correlation between δB_z and the average IMF B_z . Figure A7.2 shows equatorial distributions of the external part ΔB_z of the magnetospheric magnetic field (i.e., without the contribution from the earth's sources) for four intervals of the K_p index, from the most quiet ($K_p = 0$, top left) to the most disturbed (K_p from 6 to 7 +, bottom right).

As underlined Tsyganenko and Sitnov (2007), the plots in Fig. A7.2 correspond to zero tilt of the geo-dipole and faithfully reproduce all the main features of the equatorial magnetosphere, a compressed field on the dayside, a depression in the inner region, and an extended area of a generally weak field in the near tail. As the K_p index grows, so does the average ram pressure of the solar wind, which is manifested in the progressive compression of the magnetopause. Another feature clearly seen in the panels is a steady decrease of the magnetic field in the inner magnetosphere, with the largest effect on the nightside. In the most disturbed case, the depression greatly expands outward and its center shifts toward the duskside, manifesting the development of a storm-time PRC. In the same panel, one can also see two local positive peaks of ΔB_z in the dawn and dusk sectors of the near tail. Their origin is not clear, but it should be kept in mind that binning the data by the $K_{\rm p}$ index inevitably results in a mixture of physically different states of the magnetosphere, making it hard to interpret details of the model field and distinguish them from artifacts.

7.2.12 Binning by the IMF B_z

In Fig. A7.3 Tsyganenko and Sitnov (2007) demonstrate the effect of the IMF conditions on the equatorial field. To achieve a better spatial resolution, here Tsyganenko and Sitnov (2007) used a longer expansion of Eq. 7.40 with M = 6 and N = 8. The number of unknown coefficients in this case rose to 208. As before, four more coefficients came from four FAC modules, and one more from the "penetration" term. Therefore the total number of unknown coefficients in this version was 213. As said earlier, using the SVD method made it possible to effectively regularize the problem; in this regard, special attention was also paid to the optimal choice of the binning intervals of the IMF B_{z} , having in mind that too small subsets could result in a stronger noise and artificial features in the model field. Even though the model allowed to explicitly take into account the IMF B_{y} -related twisting of the magnetotail by a suitable field deformation (Tsyganenko, 1998), we minimized that effect by choosing only data records with IMF $|B_v| < |B_z|$. In order to more clearly resolve the effects of the IMF, its B_z component was also required to stay within a specific bin both during the current and preceding hour. Finally, in the case of positive IMF B_z an additional restriction was also imposed on the D_{st} index, namely, that ≥ -20 nT, with the purpose to eliminate intervals corresponding to storm recovery phases. With all the above limitations and precautions, the data were binned into 11 intervals of the IMF B_z , with typical numbers of records in individual subsets varying in the range from \sim 6,000 to \sim 15,000. Figure A7.3 displays plots of the magnetospheric equatorial ΔB_{7} for four selected intervals of the IMF B_{7} , in the same format as in Fig. A7.2. A striking effect, evident in the case of a large positive IMF B_7 (top left panel in Fig. A7.3) is a significant increase of the magnetic field near the magnetopause, extending over a large area and especially pronounced on the dawnside. This feature was found to be stable, in the sense that it also obtained in other realizations of the model with a different degree of the spatial resolution and, hence, it should be treated as a real effect. Its plausible interpretation is the pileup at the dayside magnetopause of the newly closed magnetic flux tubes, reconnected poleward from the cusps, and their subsequent tailward flow in the LLBL (Song and Russell, 1992; Lavraud et al., 2005, 2006, and references therein). This process is opposite to the erosion of the subsolar magnetosphere during the times of southward IMF.

As for the dawn–dusk asymmetry, a possible physical cause could be the asymmetry in the magnetosheath conditions, with larger particle densities (and, hence, elevated values of the frozen-in *B*) on the dawnside. Such an asymmetry was found (Paularena et al., 2001) in IMP-8 observations of the proton density at $X \le -10r_{\rm E}$,

made near solar maximum. A similar strong dawn–dusk asymmetry was also found by Nemecek et al. (2002) at more sunward locations ($-10 \le X \le 5r_E$) using Interball data. In the opposite case of negative IMF B_z (two bottom panels in Fig. A7.3), one clearly sees a depression in the inner magnetosphere, dramatically expanding, growing in magnitude, and shifting duskward in the extreme case with IMF $B_z < -8$ nT (right). The latter plot largely resembles the one for $K_p = 6-7+$ in Fig. A7.2. However, there is a significant and interesting difference: whereas the K_p -based plot included the area of strong compression of the field near the dayside magnetopause with $\Delta B_z \sim 30$ nT at the subsolar point, there is no such compression in the case of strongly negative IMF B_z in Fig. A7.3. Moreover, here $\Delta B_z \sim -10$ nT, so that the field is actually depressed. As mentioned Tsyganenko and Sitnov (2007), this is the well-known effect of the erosion of the dayside magnetosphere (e.g., Sibeck, 1994; Muehlbachler et al., 2005), associated with reconnection and strong FACs.

7.2.13 Main and Recovery Storm Phases

In the final set of experiments, Tsyganenko and Sitnov (2007) tested the new model for its capability to replicate specific phases of a magnetic storm. To that end, a subset of data was created by selecting a set of storms of moderate magnitude, with the peak $D_{\rm st}$ in the range between $-125\,\rm nT$ and $-50\,\rm nT$. The set covered the decade from January 1995 to December 2005 and included data for 134 events. The main and recovery phase periods were selected visually using plots of the $D_{\rm st}$ index, and the obtained lists of intervals were used for the selection of corresponding spacecraft data in the magnetosphere. In total, the main and recovery phase sets included 9,848 and 49,772 data records, respectively; the larger size of the recovery set reflects its much longer average duration, in comparison with the main phase. Figure A7.4 shows the obtained equatorial ΔB_z for these two cases, in the same format as in the previous plots. Tsyganenko and Sitnov (2007) noted that for the storm main phase conditions, even though the overall field distribution resembles that obtained for the cases of high K_p -index and the strong negative IMF B_z (bottom right panels of Figs. A7.2 and A7.3, respectively), there is some difference. First, here the depth of the inner field depression is not as great as in the former two cases, presumably, because it was chosen only moderate storms. Second, the distant field in the dayside subsolar region is not as depressed as in the case of the strong southward IMF and looks more like that in Fig. A7.2 for $K_p = 6-7+$, although one still can see a narrow wedgelike area of depressed (eroded) ΔB_z in the prenoon sector, embedded between the regions of a strongly compressed field. Finally, in all three cases ($K_p = 6-7+$, IMF $B_z < -8$, and the storm main phase) there are local positive peaks of ΔB_z on the dawnside and duskside of the near tail. The peaks are the most pronounced in the case of the storm main phase, and it is no clear explanation for that feature. In the case of the recovery phase, the ΔB_z distribution is much more regular and highly symmetric in the dawn-dusk direction. It is interesting to visualize and compare the

data-based patterns of equatorial electric currents, corresponding to the magnetic field distributions in Fig. A7.4.

Figure A7.5 displays the vectors $\mathbf{j} \sim \nabla \times \mathbf{B}$, plotted against the color-coded background indicating the magnitude of the electric current density. Immediately a striking difference is noticed between the distributions for the main and recovery phases, not only in the overall magnitude of the currents, but also in the basic configuration of the current systems. In the first case, the distribution of the j vectors has nothing to do with the traditional notion of the azimuthally closed ring current: it rather has a "hook-like" shape with the largest magnitudes in the night and dusk sectors, but with virtually no current in the pre-noon sector in the entire range of radial distances. This is in good agreement with independent particle data at synchronous distance (Denton et al., 2005), indicating a low-ion pressure in the range from 08 to 13 h MLT during the times of peak negative D_{st} . Another supporting evidence is given by ENA data: essentially all the storm-time images from IMAGE MENA and HENA show an absence of ion fluxes coming from the pre-noon sector (e.g., Brandt et al., 2002). Finally, kinetic simulations of the ring current (e.g., Liemohn et al., 2001) also demonstrate that not much of the storm-time ring current exists in the pre-noon sector. As noted by Tsyganenko and Sitnov (2007), a completely different distribution of the electric currents is established during the recovery phase (right panel in Fig. A7.5). In this case the model yields a roughly axisymmetric configuration, and there is virtually no distinction or transition region between the ring and tail current systems.

7.2.14 Field-Aligned and Equatorial Currents

Tsyganenko and Sitnov (2007) noted that it is interesting to further analyze the relative role of the equatorial and field-aligned currents (FACs) in the observed dawndusk asymmetry of the disturbed inner magnetosphere. A commonly accepted paradigm is that the storm-time duskside depression of the geomagnetic field at low latitudes is due to a PRC that develops owing to an increased convection of freshly injected particles in the evening sector (e.g., Liemohn et al., 2001). The notion of a PRC is traditionally based on a premise (dating back to Vasyliunas, 1970) that the azimuthally confined equatorial current closes via FACs in the ionosphere. A global model of the magnetic field associated with such a current was developed by Tsyganenko (2000a) and employed in Tsyganenko (2002a, b), and Tsyganenko and Sitnov (2005). In Tsyganenko and Sitnov (2007), the PRC is not introduced as a separate ad hoc module, but naturally emerges as an inherent part of the global threedimensional current system, in which the flexible equatorial currents blend with the symmetric and antisymmetric components of the Region 2 FAC. Fitting such a model to data allows one to reconstruct actual magnetic configurations and to quantitatively assess individual contributions of equatorial and FACs to the storm-time field. Figure A7.6 shows a Polar plot of the low-altitude distribution of the model FAC $j_{||} = \mathbf{j} \cdot \mathbf{B}/B$ above the northern hemisphere, for the extreme case of a strong southward IMF $B_z < -8 \,\mathrm{nT}$, corresponding to the right bottom panel in Fig. A7.3.

Negative/positive values (in nA/m^2) are shown in Fig. A7.6 by red/blue colors and correspond to outflowing/inflowing current, i.e., directed antiparallel/parallel to local B vector, respectively. Latitudinal position of the Region 1 and Region 2 zones is controlled in the model by variable nonlinear parameters defining the global scale of the corresponding three-dimensional current systems, and their best-fit values were also derived from the data. As a rule, the strength and location of both systems could be determined with confidence only for southward IMF data bins, while in the case of northward IMF the location of FAC systems was found less stable and their magnitude much smaller. In the particular case, shown in Fig. A7.6, the total inflowing Region 1 and Region 2 currents (per one hemisphere) were found equal to 2.7 and 1.9 MA, respectively. The Region 2 system included a symmetric module, providing a day-night current and thus making it possible to take into account the azimuthal rotation of the Region 2 current and, owing to its coupling with equatorial currents, replicate the PRC. This effect is clearly seen in the plot: the model Region 2 zone is rotated by $\sim 30^{\circ}$ toward dusk, in agreement with the individual values of the total current in the antisymmetric and symmetric Region 2 modules, found equal to 1.6 and 1.0 MA, respectively.

Figure 7.16 displays the radial variation of the dawn–dusk asymmetry of the inner magnetospheric field, calculated as the difference between the dusk and dawn model values of the equatorial B_z GSM component at the same radial distance $r = (X^2 + Y^2)^{1/2}$. The plots correspond to zero tilt of the geo-dipole and include the asymmetry of the total model field (solid line) as well as the partial contributions from the FAC and equatorial currents.

As seen from Fig. 7.16, the net asymmetry is negative almost everywhere (i.e., the field at dusk is more depressed than at dawn) and reaches the largest values in the innermost region $\rho \leq 3r_{\rm E}$, where the contribution from FAC is dominant. The contribution from equatorial currents is relatively small here, but grows with distance and becomes nearly equal to that from FAC in the interval between 3 and $5r_{\rm E}$. At even larger distances, the field of equatorial currents rises and turns positive at $\rho \approx 8 r_{\rm F}$. Tsyganenko and Sitnov (2007) noted that the described model does not replicate the innermost eastward part of the ring current, caused by the positive radial gradient of the particle pressure at $\rho \leq 3r_{\rm E}$ (e.g., Lui et al., 1987) for two reasons. First, the used data set does not include any magnetometer data from that region, mostly because it is much more difficult to accurately separate the external part from the total field observed at small distances, due to the rapidly growing internal field. Second, even with the upper limit in Eq. 7.40 as high as N = 8, the shortest radial wavelength in the model equals $2.5 r_{\rm E}$, which means that, even if the low-altitude data are available, the smaller-scale features would still remain undetected by the present version of the code. The above boils down to a rather trivial statement: to obtain a more accurate description of the inner field, one needs to increase the spatial resolution of the model (which is the simplest task) and add new data from the innermost magnetosphere (a harder problem).



Fig. 7.16 Illustrating the dawn–dusk asymmetry of the equatorial B_z in the case of the strong southward IMF. The difference $B_z^{(dusk)} - B_z^{(dawn)}$ is plotted as a function of the radial distance along y_{GSM} -axis. Solid, dashed, and dotted lines correspond to the total external field and to the individual contributions from the FACs and equatorial currents, respectively (From Tsyganenko and Sitnov, 2007)

7.2.15 "Penetrating" Field Effect

As noted by Tsyganenko and Sitnov (2007), another interesting feature of the model field is the dependence of the "penetration" term $\delta B_z \mathbf{e}_z$ on the IMF B_z . It was found that adding that term resulted in a significant (3–4%) improvement of the fit, especially in the case of a strong southward IMF. Its magnitude δB_z was also treated as an unknown model parameter and was found along with other parameters for 11 data subsets, corresponding to consecutive intervals of the IMF B_z . Figure 7.17 shows the variation of δB_z against IMF B_z , revealing a strong correlation between these quantities.

According to Tsyganenko and Sitnov (2007), two features deserve to be noted. First, there is virtually no difference in the slope of the curve between the positive and negative IMF B_z , which one might expect based on the notion of the magnetosphere as a "rectifier" that selectively responds to opposite polarities of the IMF B_z . Second, the plot has a small negative intercept at IMF $B_z = 0$, equal to $\sim -2 \text{ nT}$, which would make it more difficult to interpret the field δB_z as a penetrated IMF, since in that case one would run into a paradoxical conclusion that positive IMF B_z



Fig. 7.17 The best fit "penetrating" field δB_z as a function of the IMF B_z (From Tsyganenko and Sitnov, 2007)

penetrates in the magnetosphere as a negative δB_z . In the opinion of Tsyganenko and Sitnov (2007), the easiest interpretation of this term is related to the fact that the considered magnetopause model does not depend on the IMF B_z , but responds only to the solar-wind dynamic pressure. In actuality, the average magnetopause significantly changes its shape with the varying IMF B_z (Shue et al., 1998), and that can be a primary factor behind the obtained dependence of δB_z on the IMF conditions. Introducing the variable shape of the model magnetopause still remains a major challenge in the empirical modeling, to be resolved in a future work.

7.2.16 Effects of the Dipole Tilt and IMF B_y on the Model Tail Current

As noted by Tsyganenko and Sitnov (2007), seasonal and diurnal variations of the earth's dipole tilt angle Ψ with respect to the X = 0 plane result in a periodic transverse motion and large-scale deformation of the tail current sheet. This effect has been known since long (Russell, 1972); the most recent quantitative model providing the shape of the tail current sheet as a function of Ψ and concurrent interplanetary parameters was devised by Tsyganenko and Fairfield (2004). As shown in that work and in an earlier study (Tsyganenko, 1998), the net deformation of the originally planar current sheet can be represented as a superposition of bending in the X-Z plane, warping in the Y-Z plane, and twisting around the x-axis. The former two deformations are due to the dipole tilt, while the latter one is associated with the IMF B_{y} component. A complete quantitative description of the model field deformations needed to incorporate these effects was given in Tsyganenko, (2002a). The work of Tsyganenko and Sitnov (2007) uses essentially the same procedure. Figure A7.7 displays the shape of the deformed model current sheet for the dipole tilt angle $\Psi \Box = 30^{\circ}$ and two opposite polarities of the IMF B_z : strong and positive/negative in the left/right panels, respectively. To illustrate the IMF B_y -related deformation, a clockwise twisting by the angle 30° was added in the right panel. The goal of Tsyganenko and Sitnov (2007) was to demonstrate the geometry of the deformation, rather than the absolute magnitude of the current. For that reason, the color scale for the current volume density was saturated at the upper end and, even though the total current in the right panel is much larger, the plot does not the reproduce that difference. Regarding the shape of the current sheet, it is interesting to note a significant difference in the degree of the warping: in the case of IMF $B_z < -8$ nT the current sheet is much closer to a planar one, than in the case $B_z > +8$ nT. This agrees well with the earlier conclusion of Tsyganenko and Fairfield 2004), that under southward/northward IMF conditions the tail current sheet becomes more "rigid/elastic" with respect to the tilt-induced deformations.

7.2.17 Summary of Main Results

Summarizing obtained results, Tsyganenko and Sitnov (2007) came to the following conclusions.

- 1. A new method has been introduced and developed of reconstructing the global geomagnetic field from spacecraft data, using a high-resolution extensible approximation for the field of equatorial currents.
- 2. The model naturally and flexibly couples the equatorial and FACs and thus makes it possible to represent with any desired resolution global distributions of the geomagnetic field for different conditions in the solar wind and in the magnetosphere, provided a sufficient coverage by spacecraft data is available.
- 3. A new database of spacecraft magnetometer data has also been compiled, and the high-resolution model has been calibrated against various subsets of that database.
- 4. The obtained detailed maps of the magnetic field reveal all the principal elements of the magnetospheric structure, their dependence on the interplanetary conditions, and the basic changes associated with principal phases of a magnetic storm. Specifically, the model reveals the following features: (1) compressed field on the dayside, growing in magnitude with increasing solar wind pressure; (2) strong erosion of the field in the sub-solar region during the times of large southward IMF, driving the storm main phase; (3) depression of the inner magnetospheric field, whose depth and dawn-dusk asymmetry dramatically grow during stormtime periods; (4) extended region of weak equatorial field in the near tail, increasing toward the tail's flanks, especially for strong northward IMF conditions; (5) strong correlation of the "penetrating" δB_z with the concurrent IMF B_z ; (6) strong increase of the current in the post-midnight and evening sectors at the storm main phase, accompanied by its dramatic reduction in the entire pre-noon sector and resulting in a hook-like shape of the overall pattern of the storm-time equatorial current; and (7) fairly broad and virtually axisymmetric equatorial current for the storm recovery phase, without any significant distinction between the ring and tail current systems.

7.3 Storm-Time Configuration of the Inner Magnetosphere

- 5. The presented method can be likened to making a snapshot of the magnetosphere with a camera, with a similar trade-off problem as in photography: to get a good image, one needs a long enough exposure (in our case, a sufficiently dense coverage of the magnetosphere by the data). On the other hand, too long an exposure may result in smearing and loss of important details because of the finite rate of the object's temporal evolution.
- 6. A perfect source of data to be used with this technique would be a Constellationclass mission (Angelopoulos et al., 1998), intended to provide dense grids of observation samples for any given time interval. Nevertheless, as demonstrated in this study, even with already available sets of data from many spacecraft and rather simple data-binning procedures it is possible to discern basic features of the magnetospheric structure/dynamics, as well as new interesting effects, such as the significant increase of the near-magnetopause field during strong northward IMF conditions.
- 7. Even without the Constellation-level data resource, described in the method of Tsyganenko and Sitnov (2007) can significantly improve the spatial resolution of the models like Tsyganenko (2002a,b) and Tsyganenko and Sitnov (2005). A promising approach in this regard is to advance the conventional data binning procedures by using modern techniques of time series processing, such as the nearest-neighbors and time delay embedding, successfully employed in the nonlinear modeling and prediction of global magnetospheric parameters (e.g., Vassiliadis et al., 1995; Ukhorskiy et al., 2004). That would make it possible to fully implement the described new technique of Tsyganenko and Sitnov (2007) in the empirical models and bring them to the level of forecasting tools.

7.3 Storm-Time Configuration of the Inner Magnetosphere: Lyon–Fedder–Mobarry MHD Code, Tsyganenko Model, and GOES Observations

Huang et al. (2006) compare global magneto-hydrodynamic (MHD) simulation results with empirical models and observations to understand the magnetic field configuration and plasma distribution in the inner magnetosphere, especially during geomagnetic storms. The physics-based Lyon–Fedder–Mobarry (LFM) code simulates the earth's magnetospheric topology and dynamics by solving the equations of ideal MHD. Quantitative comparisons of simulated events with observations reveal strengths and possible limitations and suggest ways to improve the LFM code. Huang et al. (2006) present a case study that compares the LFM code to both geosynchronous measurements from GOES satellites and the Tsyganenko et al. (2003) semi-empirical magnetic field model (noted as T03) which aptly reproduces the stormy magnetosphere.

As underlined Huang et al. (2006), the series of Tsyganenko models are empirical magnetic field models. They reproduce the global average of dynamic states of the earth's magnetosphere, based on large quantities of spatially distributed satellite measurements and flexible parameters. The Tsyganenko models have evolved along with the progressive knowledge of space physics. The earliest Tsyganenko models (Tsyganenko and Usmanov, 1982; Tsyganenko, 1987, 1989) represented the global distribution of the average magnetic field as a function of the $K_{\rm p}$ index. Over time, the models have improved to include explicit representations of the Region 1 and 2 Birkeland current systems, SRCs and PRCs, and a warped tail current sheet. Physically relevant quantities, including the upstream solar wind and IMF, and the D_{st} index, parameterize the current models. The model data-fitting method has also advanced with time, from the amplitude of the external field sources being dependent linearly on solar wind inputs, to nonlinear saturation of these sources during extreme conditions. Tsyganenko models provide global static views of the earth's magnetosphere which mimic the time-evolving magnetosphere with minimal computer time. However, because these models are data-based and because extreme conditions are rare, model users should be especially cautious when using these earlier model versions for large storm events. The Tsyganenko et al. (2003) model (noted as T03) apply reproduces the stormy magnetosphere. The magnetic field data set of this recent model T03 includes 37 storm events that occurred between 1996 and 2000, using most of the available satellite data in the inner magnetosphere. In addition to solar-wind data and the D_{st} index, this new model also uses time-integration indices (G2 and G3) as inputs to capture the geomagnetic coupling effects between the solar wind and the magnetosphere. The magnetosphere responds nonlinearly during strongly disturbed intervals, so nonlinear fitting methods treat the saturation characteristics during extreme conditions. Both of the time-integration effects and the nonlinear interpolation of the current calculation limit the growth of the field sources for active conditions.

The storm event Huang et al. (2006) selected for thorough examination is a magnetic-cloud-associated storm during September 24–26, 1998. It is a storm selected for study by the GEM community and has features of typical major storms. Figure A7.8 shows the solar-wind conditions and the D_{st} index for this event. The top and middle panels of Fig. A7.8 show solar-wind number density, velocity, and ram pressure, and IMF components in GSM coordinates, measured by the Wind spacecraft at ~180 r_E upstream (180, 15, and 10 r_E in GSM Cartesian coordinates). Using the D_{st} index (bottom panel) as an indication of storm event evolution, this event has typical storm features. The solar-wind pressure pulse arrived slightly before September 25 and produced a classic SSC.

Figures A7.9 and A7.10 show the magnetic field comparisons of GOES 8 and 10 data, the T03 model, and the MHD simulation results during the September 1998 storm event.

In Figs. A7.9 and A7.10 the top three panels are the vector components of the magnetic field in dipole coordinates and the bottom two panels are the magnetic field magnitude and elevation angle. Elevation angle is defined such that $90^{\circ}(0^{\circ})$ means the field line is perpendicular (parallel) to the equatorial plane. The black lines are the measurements from GOES satellites after correcting the systematic offset. The red lines are the predicted values of the Tsyganenko et al. (2003) storm model at the GOES positions using time-dependent upstream solar-wind inputs from the Wind

satellite and the D_{st} index. The green lines are the fields predicted by the LFM code MHD simulation at the same GOES locations using the same solar-wind inputs. During most of the quiet periods, before the storm and during the recovery phase, the predictions of the LFM code MHD simulations and the T03 model agree with the observed fields fairly well. However, the predictions are not as good during the storm main phase (September 25, 1998, 00:00-12:00 UT) and particularly when GOES satellites are on the nightside (September 25 and 26, early UT day). In terms of field component magnitudes, the T03 model predicts the storm time magnetic fields better than LFM during most of the storm interval, except the Y component during storm main phase. The MHD simulations predict lower (higher) magnitude for the X(Z) component and a good fit for the Y component. The MHD simulations are able to reproduce the small timescale variations driven by the solar wind much better than the T03 model, especially during storm main phase in the Z component. In the elevation angle plot, the MHD simulations predict constantly higher angles throughout the event. This indicates the MHD field lines at geosynchronous orbit are not stretched enough compared to observations and the T03 model, especially during storm main phase and on the nightside.

As noted Huang et al. (2006), Figs. A7.9 and A7.10 demonstrate that the LFM code has certain strengths and weaknesses in reproducing magnetic fields of a major magnetic storm at geosynchronous orbit. Comparison with GOES data shows how well the MHD simulations predict the field at one point as a function of time, but not its global performance. To investigate the ability of the MHD simulations in reproducing the storm time inner magnetosphere at all local times and throughout the inner magnetosphere, Huang et al. (2006) next study the simulation results globally within the model domain based on the knowledge that the T03 model predicts the magnetic field very well at geosynchronous orbit and that it was constructed with and constrained by measurements made throughout the entire inner magnetosphere volume. Therefore, Huang et al. (2006) assume that it predicts well everywhere in the inner magnetosphere and they use the T03 model as a proxy for global simultaneous observations. To compare the field topology of both global models, Huang et al. (2006) trace magnetic field lines at all local times. Panels a and b in Fig. A7.11 are three-dimensional magnetic field configurations viewed from dawn at an angle above the equator, before the storm (top panel a, 13:59 UT 24 September 1998) and during the main phase (bottom panel b, 05:22 UT 25 September). Representative field lines of the MHD simulations (green curves) and the T03 model (red curves) are traced from points on a 6.6 r_E-circle on the GSM equatorial plane, and at eight equispaced local times. The tick marks on the X and Y-axes are 10 $r_{\rm E}$ apart. The sun is toward the right in both panels.

As underlined by Huang et al. (2006), before the storm, the MHD simulations and the T03 model have very similar dipole-like field configurations; the T03 model field lines are only slightly more stretched than the MHD simulation result. During storm main phase, both the MHD and T03 fields stretch more relative to prestorm conditions. However, the MHD magnetic field lines are not as stretched as the T03 model at all local times, especially on the nightside. On the dayside, the MHD open field lines indicate the magnetopause location moves into 6.6 $r_{\rm E}$. Since

the occurrence of major storm events (D_{st} minimum < -200 nT) is low and the data needed to construct empirical models are sparse, it is very difficult to predict empirically the magnetospheric magnetic fields during extreme conditions. Overdriving the parameterized ring current or tail current during large storms can even create artificial sites of reconnected field lines in the inner magnetosphere or unrealistic stretched field lines. To understand more quantitatively the field configuration differences between the T03 model and the LFM code, Huang et al. (2006) next explore the near-equatorial current and pressure gradient distributions in these models during storm main phase. Panels a and b in Fig. A7.12 show the current systems calculated from the T03 model and the MHD simulation at the equatorial plane during the storm main phase (05:22 UT September 25, 1998). Current magnitudes perpendicular to the local magnetic field are shown, calculated from both models by taking the curl of the local magnetic field $J_{\perp} = |(\nabla \times B) \times B| / \mu_0 |B|$ according to Ampere's Law (with $dE/dt \sim 0$). The color scales of these two current maps are the same and range from 0 to 10 nA/m^2 , with a $1.5 \times 1.5 r_{\text{E}}$ data smoothing. The white dashed lines denote the location of geosynchronous orbit, centered on earth. For the MHD simulation, a ring-current-like feature builds up on the nightside during storm main phase, where and when the field lines become more stretched from their original dipole-like shape. Nevertheless, the intensity is too weak to reduce the simulation field strength and yield enough stretching as was observed.

As noted by Huang et al. (2006), if the models are in magneto-hydrostatic equilibrium and the slow flow approximation applies to the inner magnetosphere, then one can assume that the $J \times B$ force balances the plasma pressure gradients. Previous studies showed that Tsyganenko models are approximately consistent with pressure balance (Spence et al., 1987; Lui et al., 1994; Zaharia and Cheng, 2003). Panels c and d in Fig. A7.12 are maps of the plasma pressure gradient $\nabla P = |J \times B|$ calculated in both models. At geosynchronous orbit, as with the current systems, the MHD simulation has weaker pressure gradients than the T03 model at all local times. Several limitations inherent to the LFM code may contribute to these differences. The MHD simulation does not include ionospheric outflow, which is a major heavy ion plasma source during storms. In addition, the MHD simulation is a single-fluid and therefore does not contain energetic ring-current particles; particles in this non-thermal part of the distribution can carry much of the energy density in the inner magnetosphere during storm time. Huang et al. (2006) note that sunward $E \times B$ drifts create some pressure pile up in the inner magnetosphere in the MHD simulation. However, only gradient and curvature B drifts can support and maintain a realistic, asymmetric ring current around the earth.

Huang et al. (2006) came to following conclusions:

- 1. Huang et al. (2006) study compared LFM MHD code results with the Tsyganenko et al. storm model and the GOES observations in order to understand the storm-time configuration of the inner magnetosphere and the performance of global MHD simulations.
- The physics needed to describe fully the evolution of the inner magnetosphere magnetic fields and plasma during magnetic storms is complicated and difficult to simulate. The limitations of global MHD codes, such as not including

important nonideal MHD physics, underspecified initial and boundary conditions, and demand on computational resources, constrain their ability to reproduce the time-dependent magnetosphere accurately. Therefore it is important to validate the MHD simulations with observations to understand and quantify the practical limits of the global codes (Ridley et al., 2002; Spence et al., 2004).

- 3. Huang et al. (2006) noted that the Tsyganenko et al. (2003) storm model overall reproduces the magnetic field at geosynchronous orbit very well throughout the entire September 25–26, 1998 storm. The greatest difference between the model prediction and data is \sim 50nT during storm main phase, but with differences generally much lower. The T03 model predicts the geosynchronous fields better than the MHD simulations even for several storm events not included in T03 model data set.
- 4. However, the Tsyganenko models are temporally and spatially averaged views of the dynamic magnetosphere, so they do not reproduce small timescale field variations as well as the MHD simulations. Even though constructed from sparse satellite data in time and space, the T03 model describes the storm-time field configuration of the inner magnetosphere with impressive success. Nevertheless, outside the model spatial domain and during extreme conditions, model users should use it with caution. In regions and conditions of validity, the T03 model provides useful baseline predictions of the inner magnetosphere to evaluate the accuracy of MHD simulations.
- 5. Huang et al. (2006) explored LFM model performance through case study analysis. During the September 1998 storm (D_{st} minimum of -213 nT) both the LFM code and the Tsyganenko et al. (2003) model T03 predict well the magnetic field strength and basic variations throughout the event, when compared with the observed fields from the GOES 8 and 10 satellites. The T03 model predicts the magnetic field better than the MHD simulation in B_X and B_Z components. However, the LFM code better simulates the more rapid magnetic field fluctuations that result from variable solar-wind driver inputs.
- 6. Comparing the magnetic field configurations, the T03 modeled field lines stretch more than the MHD simulated field lines, particularly on the nightside and during the storm main phase. Pressure gradient maps (inferred from maps of $J \times B$) show that the MHD simulation has an insufficient current system in the inner magnetosphere and overestimates the field strength (by as much as ~100 nT in the B_Z component) during storm main phase.
- 7. To assess whether features seen in the case study are persistent trends, Huang et al. (2006) also performed statistical comparisons. In the statistical study, there are compared the MHD results of nine magnetic storms and a 2-month-long simulation with geosynchronous satellite measurements. For non-storm periods $(D_{st} \ge -20 \,\text{nT})$, the MHD simulated magnetic fields in the X and Y components are comparable to the observed fields, being well within $\pm 10 \,\text{nT}$. The simulated Z component systematically differs from observations by $\sim 10 \,\text{nT}$ on the dayside and $\sim 30 \,\text{nT}$ on the nightside. Under storm conditions $(D_{st} < -20 \,\text{nT})$, the residual fields between the simulations and observations follow the same trends but are even larger, especially on the nightside.

7.4 Magnetospheric Transmissivity of CR Accounting Variability of the Geomagnetic Field with Changing K_p and with Local Time (Within the Frame of the Tsyganenko-89 Model)

7.4.1 The Matter of Problem

Kudela and Usoskin (2004) summarize computations of CR trajectories mostly within the frame of the Tsyganenko-89 model of the geomagnetic field (see Section 7.1) for a high-latitude NM station (Oulu) and a middle-latitude one (Lomnicky Štit). The method is slightly different from previous computations (described in detail in Chapter 3) by controlling the smoothness of the trajectory. At the lowest rigidity edge of allowed trajectories for Oulu (above the atmospheric CR cutoff), the external field and the addition of D_{st} shows variations of the asymptotic directions with the level of geomagnetic activity and with local time of observations. The transmissivity function (TF), determined in (Kudela and Usoskin, 2004), accounting variability of the magnetic field with changing K_p and with local time, may be used as a reference to describe the average magnetospheric transparency at middle latitudes. There are indications of the appearance of windows of allowed trajectories at very low rigidities in the middle latitudes at 500 km altitude (e.g., CORONAS satellites or ISS) during a geomagnetic disturbance, which is not the case for trajectories computed from the ground.

Kudela and Usoskin (2004) noted that the details of CR transport in the earth's magnetosphere, to access ground CR stations or low-altitude satellites, have long been studied (McCracken et al., M1962, M1965; Shea et al., M1976; see in detail, Chapter 3). The main tool for this study is the numerical back-tracing of the CR particle's trajectory in a geomagnetic field model. The trajectory starts from the observational site and is traced back by reversing the particle's velocity vector and the sign of charge. The computed trajectory is regarded as allowed, if it crosses the magnetospheric boundary, and as forbidden, if the trajectory rests on the earth's surface, or trapped, if it remains within the magnetosphere for a long time. Progress of CR trajectory computations in the geomagnetic fields has been summarized recently in Smart et al. (2000). Between the allowed and forbidden ranges of a particle's rigidity, there is an area of complicated intermittent structure, the penumbra. From the penumbra structure, the following concepts of cutoff rigidity can be identified (Cooke et al., 1991): lower cutoff, $R_{\rm L}$, is the rigidity, below which all trajectories are forbidden, upper cutoff, $R_{\rm U}$, is the rigidity above which all trajectories are allowed, and the effective rigidity cutoff, $R_{\rm C}$. It is usual to characterize a given site by its vertical effective cutoff. The vertical cutoff rigidities computed for various epochs in the internal geomagnetic field are summarized in Shea and Smart (2001). In addition to the internal geomagnetic field, external field models were used for the trajectory computations of CRs in several papers Flückiger and Kobel, 1990; Danilova and Tyasto, 1995; Kudela et al., 1998). Introducing an external magnetic field model, which assumes the varying current systems within the magnetosphere and near its boundary regions, provides a better approach to the description of the

CR cutoffs, the structure of penumbra and of the asymptotic directions. Sometimes the classical approach fails to explain observational facts. For example, it has been recently found that there is a significant difference in count rates of NM with close asymptotic directions (e.g., Oulu and Apatity) during an anisotropic phase of GLE that occurred during 14–16 h of the local magnetic time (Vashenyuk et al., 2001). Including the external field for low-altitude satellites improves the agreement between computed and measured positions of cutoff latitudes, although a difference of $\approx 1^{\circ}$ still remains (Smart and Shea, 2001). Therefore, computations of trajectories, using different approaches are still important for the description and understanding of the magnetospheric transmissivity of CRs.

Kudela and Usoskin (2004) introduce a method of trajectory computations and compared it with earlier results. They describe the effects of the external-field model (Tsyganenko, 1989) and its extension with including D_{st} , according to Boberg et al. (1995), which is found to be relevant for NM measurements at high (Oulu) and a middle (Lomnicky Štit) latitude stations as well as for low-altitude satellites. They also tested the stability of the trajectory and consequent cutoff computations versus uncertainties of the magnetic-field models. The found TFs can be used as an additional reference to the concepts of lower, effective and upper CR cutoffs at middle latitudes. For example, such an approach may be applied for determining CR cutoff rigidities for the low-orbiting International Space Station.

7.4.2 The Calculation Method

The model magnetic field used in Kudela and Usoskin (2004) is a superposition of the DGRF model including all harmonics up to the order of 10 and of the Tsyganenko-89 external-field model (Tsyganenko, 1989; see Section 7.1) according to the numerical scheme (Peredo and Tsyganenko, 1993) magnetospheric boundary is taken as follows: the shape of the magnetopause is approximated by the form of Sibeck et al. (1987) for the dayside ($X_{GSM} > 0$), while the border is fixed at a distance of $25r_{\rm E}$ for the nightside ($X_{\rm GSM} < 0$). The calculated asymptotic directions are given in the GEO coordinate system. Using the magnetopause model on the dayside gives the information whether the traced CR particle accesses the magnetosphere from the dayside or not. The nightside boundary is taken as a sphere of $25 r_{\rm E}$ radius similarly to earlier calculations by other authors (e.g., Shea et al., 1965; Shea and Smart, M1975) who used $25 r_E$ boundaries for all sectors of local time. In such an approach there is, however, a discontinuity at X = 0. For each crossing of X = 0 between two subsequent points of the trajectory, Kudela and Usoskin (2004) distinguished the sense of the direction: if X > 0 at the latter point then the distance is compared to $25 r_{\rm E}$, and if X < 0, the position is checked with respect to the magnetopause dayside model. The IGRF field model used in Kudela and Usoskin (2004) is adopted from Langel (1992) and from http://nssdc.gsfc.nasa.gov/space/models/igrf.html. The transport equation of a charged particle in the geomagnetic field is solved numerically by Runge-Kutta

Table 7.1 The effective vertical cutoff rigidities (in GV) for two stations (The effective Oulu, 65.05°N, 25.47°E; Lomnicky Štit, 49.20°N, 20.22°E), epoch 1985, computed using the IGRF model only, with a different maximum number of computational steps N for $T = 10^{-3}$ rad. The last column is from Table 7.1 of Shea and Smart (2001) (From Kudela and Usoskin, 2004)

Station	Ν						From Shea and
	$2.5 imes 10^4$	$5 imes 10^4$	10 ⁵	2×10^5	$5 imes 10^5$	10 ⁶	Smart (2001)
Oulu	0.85	0.83	0.79	0.77	0.76	0.76	0.76
Lomnicky Štit	4.25	4.16	4.10	3.96	3.94	3.94	3.95

method of the sixth order. The elementary computational step along the trajectory is taken as $2\pi r/n$, where r is the particle's gyro-radius (in the local magnetic field) and n is initially taken as 100. During computations both the conservation of the particle's velocity modulus and smoothness of the trajectory were controlled. If the deviation of v (velocity vector) in two subsequent points of the trajectory exceeds a preselected value T at some elementary computational step, then this step is recalculated with the halved length. If the trajectory is not resolved as forbidden or allowed after the preselected number N of elementary computational steps, then it is regarded as forbidden. Then the value of $R_{\rm C}$ is computed from the system of forbidden and allowed trajectories. Backward computations start from the point with an altitude of 20 km above the observational site in vertical (radial to the earth's center) direction assuming the spherical shape of the earth with an average radius of 6371.2 km. As an example, Table 7.1 shows the effective vertical cutoff rigidities computed using IGRF only, for Oulu and Lomnicky Štit for different values of N when T is fixed in comparison with those obtained in Shea and Smart (2001) for the epoch 1985.

Although the methods used in Kudela and Usoskin (2004), and in Shea and Smart (2001) are based on different numerical schemes of trajectory tracing, there is good agreement in the CR effective vertical cutoffs. One can see from Table 7.1 that the increasing of *N* above 2×10^5 results in only a small additional decrease of the calculated CR cutoffs, due to resolving a few more low-rigidity quasi-trapped trajectories as allowed ones. Moreover, the upper cutoff value R_U is stable for both stations for $N > 10^5$. Therefore, Kudela and Usoskin (2004) use $N = 2 \times 10^5$ in the following calculations of TFs for both CR stations.

7.4.3 Calculations of Transmissivity Functions

Details of the magnetospheric transparency for CR can be described by a transmissivity function *TF* (*R*, *LT*, *Kp*, *D*), where *R*, *LT*, *K*_p, and *D* are the particle's rigidity, local time, K_p index, and the day of the year, respectively. In Kudela et al., (1998) the seasonal variation of the CR cutoffs for Lomnicky Štit was examined and found that it is much less than the diurnal variability of the cutoffs. Accordingly, Kudela and Usoskin (2004) neglected the seasonal variation. The TF is defined as the probability of a primary particle with rigidity in the interval [R, R + dR] to vertically access the position above the measurement site at a given local time *LT* during the time, when geomagnetic activity is characterized by the K_p index. TF is calculated as the ratio of the number of allowed to (allowed + forbidden) trajectories within the rigidity interval [R, R + dR]. Kudela and Usoskin (2004) noted that, although calculation of each trajectory is unambiguous within the frame of the deterministic computational model, some uncertainties and random fluctuations are always present in the real magnetosphere. The TF is defined in a probability sense, which is more natural taking into account the real uncertainties. Usually, the count rate *N* of any NM is given as follows:

$$N = \int_{R_{\rm c}}^{\infty} D(R) Y(R) \,\mathrm{d}R,\tag{7.45}$$

where D(R) and Y(R) are the differential spectrum of CR at the earth's orbit and the specific yield function of NM (in Dorman, M1957, this function was called "integral multiplicity" which means total number of secondary particles detected by NM, generated from one primary CR particle of rigidity R), and R_C is the effective rigidity cutoff. Using the TF, the count rate N is now given as

$$N = \int_{0}^{\infty} TF(R)D(R)Y(R) dR.$$
(7.46)

Let us note that similar function was introduced and widely used in Dorman (M1971, M1972) and in Dorman (M1975b, M2004), where it was called "penumbra function." Hofer and Flütkiger (2000) introduced in similar manner the "geomagnetic filter function" in analyzing a Forbush decrease.

While Eqs. 7.45 and 7.46 yield very similar results on average, it appears important to use the TF approach in some particular cases as will be discussed later. Kudela and Usoskin (2004) also note that the difference between Eq. 7.45 and Eq. 7.46 may be significant for solar CRs with a soft energy spectrum. Using different elementary steps in rigidity for the trajectory computations (ΔR ranging from 10^{-3} to 10^{-5} GV) in the interval 0.4–0.8 GV, Kudela and Usoskin (2004) found that refining the rigidity resolution below 10^{-4} GV does not significantly change the shape of TF and for practical purposes the value of $\Delta R = 10^{-3}$ GV is sufficient (Bobik et al., 2001).

7.4.4 Asymptotic Directions for a High-Latitude Station

In Kudela and Usoskin (2004), the transmissivity of CRs through the magnetosphere to the Oulu NM (65.05° N, 25.47° E) was calculated. It was taken into account that the vertical effective cutoff rigidity of Oulu NM is close to the atmospheric
cutoff assuming the response function of a NM near the sea level (e.g., Nagashima et al., 1989; Dorman et al., 2000; see also in detail Chapter 3 in Dorman, M2004, and Chapter 5 in this volume). Figure 7.18 depicts the fine structure of asymptotic directions within the penumbra at the position of Oulu.



Fig. 7.18 Asymptotic directions computed for Oulu NM with the rigidity step $\Delta R = 10^{-5}$ GV, as for January 21, 1986, 12 UT, low K_p (*IOPT* = 1 in the Tsyganenko-89 model; see Section 7.1). The *upper* panel shows the angular difference between the asymptotic directions of the two consecutive allowed trajectories. The lower three panels display the distance to the entry point r_{ep} in r_E , and asymptotic longitude and latitude defined by Shea and Smart (M1975) (From Kudela and Usoskin, 2004)

The fine structure of the penumbra and its implications for a high-latitude NM count rate was also studied in Pchelkin and Vashenyuk (2001). Although the structure of the penumbra at high latitudes is not expected to significantly affect the count rate of a ground NM, its implications for energetic particle measurements onboard low-altitude polar orbiting satellites may be important. One can see from the top panel of Fig. 7.18 that the neighboring allowed trajectories are spread widely and randomly in their asymptotic directions as d α is large and has no regular pattern vs. R at $R < 0.675 \,\text{GV}$. The divergence of the neighboring trajectories, d α , is not reduced with increasing ΔR , which implies that the model becomes unstable. For rigidities in the range from 0.75 to 0.81 GV, many trajectories are close to each other (small d α values), but these regular structures are intermitted by areas with a large divergence of the neighboring trajectories. Kudela and Usoskin (2004) have studied this transition (from random to regular patterns of trajectories) range in more detail. The lower panels of Fig. 7.18 show the asymptotic directions for the rigidity range 0.67–0.70 GV. One can see that among random large fluctuations, there are intervals of rigidity with regular smooth changes of the asymptotic direction (e.g., 0.676–0.677 GV or 0.692–0.694 GV). These intervals correspond to the entry in the dayside sector, while intervals of chaotic behavior of the asymptotics are mostly related to the nightside entries. Similar intervals of regular changes were also found in the penumbra for the middle-latitude station Lomnicky Štit). This fact is likely to be related to a more complicated character of the low-rigidity particle's trajectories in the geomagnetic tail and to a more complicated geometry of the nightside magnetosphere (Pulkkinen and Tsyganenko, 1996) than analytical models predict. Limitations of empirical magnetic-field models have been mentioned earlier (see, e.g., Stern and Tsyganenko, 1992; Peredo et al., 1993; and references therein). In particular, large fluctuations of the observed values of B_7 near the neutral sheet of magnetosphere with respect to the model value have been reported even during times of low geomagnetic activity ($K_p < 2$). Kudela and Usoskin (2004) have estimated the effect of uncertainties in the magnetic-field modeling on the computation of CR trajectories for the Oulu position for two cases: one with $(B_z + 10)$ nT and the other one with $(B_z - 2)$ nT in the tail central region for $X < -10r_E$, which corresponds to the spread of experimental points in Fig. 4 of Kudela and Storini (2002). The geomagnetic conditions were fixed to quiet ones (IOPT = 1).

The values *IOPT*, used in Kudela and Usoskin (2004), are taken according to the Tsyganenko-89 model (Tsyganenko, 1989; see also Section 7.1): *IOPT* = 1 for $K_p = 0,0+$; *IOPT* = 2 for $K_p = 1-$, 1, 1+; *IOPT* = 3 for $K_p = 2-$, 2, 2+; *IOPT* = 4 for $K_p = 3-$, 3, 3+; *IOPT* = 5 for $K_p = 4-$, 4, 4+; and *IOPT* = 6 for $K_p \ge 5-$. Calculations were made for two fixed times (12 and 00 UT), and no notable changes in the values of R_L , R_C , nor R_U , related to the spread of B_z , were found. However, the employed variations of B_z resulted in significant changes of the asymptotic directions for many trajectories. For midnight, this affects only particles with the rigidity below 0.734 GV, and changes of asymptotic directions range from 30° to 80°. The effect of changing B_z is much more significant during the noontime as it affects rigidities of up to 1.2 GV. This may even be significant for

Table 7.2 Effective vertical cutoffs (in GV) for Oulu calculated using the Tsyganenko-89 field model and with D_{st} extension by the method of Tsyganenko (1989) added to *IOPT* = 6. Date is January 21, 1986 (From Kudela and Usoskin, 2004)

UT		Magnetic activity						
	IOPT = 1	IOPT = 6	$D_{\rm st} = -100{\rm nT}$	$D_{\rm st} = -300 nT$				
00	0.619	0.252	0.129	0.051				
06	0.672	0.487	0.407	0.197				
12	0.647	0.413	0.346	0.169				
18	0.610	0.253	0.159	0.051				

the ground-based observations of an anisotropic flux of CRs (see, e.g., Vashenyuk et al., 2001). For a better understanding of the nightside particle entry the geomagnetic tail model should be extended to larger distances than the border adjusted here (and in earlier computations by other authors).

Kudela and Usoskin (2004) have also studied variations of the effective vertical cutoff rigidity versus the time of observations and versus the level of geomagnetic activity. We performed a set of calculations for different times with 2-h steps for low (*IOPT* = 1) and high (*IOPT* = 6) levels of geomagnetic activity as well as for the two levels of D_{st} . The rigidity step was fixed to $\Delta R = 10^{-3}$ GV. The results are shown in Table 7.2.

In all computations, where the epoch is not explicitly mentioned, the internal field is taken for January 21, 1986. An increase of the geomagnetic activity causes a depression of the calculated cutoff. The smallest depression was found around 06 UT in all cases, while the deepest one is expected in the afternoon and night sectors. The computations indicate that most of the trajectories, which change their status from forbidden (or quasi-trapped) at low geomagnetic activity to allowed at high activity, enter the magnetosphere from the nightside. The asymptotics are concentrated eastward of the station's site, making access more difficult during the local morning. However, since the depressed rigidity cutoff is well below the atmospheric cutoff (about 0.8 GV), an increase of the magnetospheric transparency during geomagnetic storms is insignificant for high-latitude stations, geomagnetic activity variations influence the asymptotic directions at the low-rigidity range above the atmospheric cutoff (see Fig. 7.19).

A clear illustration of this effect is the geomagnetic storm on March 30–31, 2001, when a large increase of count rate associated with the decrease of their cutoffs was found at the middle- and low-latitude stations, while the count rate of high-latitude stations in both hemispheres (Oulu and Sanae) was continuously decreasing, corresponding to the time profile of the intensity of primaries outside the magnetosphere (Kudela and Storini, 2002). As seen from Fig. 7.19, for low geomagnetic activity (IOPT = 1), the asymptotic directions are only slightly changed with the local time except for a north–south asymmetry seen at the lowest *R* in noon–midnight



Fig. 7.19 Asymptotic directions of (0.8–1.5) GV primary CRs vertically accessing the position of Oulu NM at midnight and noon for different geomagnetic conditions. The date is January 21, 1986 for the internal field. The arrows depict the asymptotic directions corresponding to 0.8 GV in all cases. Rigidity 1.5 GV corresponds to the other end of the line (From Kudela and Usoskin, 2004)

comparison. However, the asymptotic directions shift significantly westward and their range is narrowed with increasing geomagnetic activity, especially in the midnight sector. The shift in longitude is more than 90° for IOPT = 6 and exceeds 150° for $D_{st} = -300$ nT. These effects, especially the narrowing of the acceptance direction interval during strong geomagnetic disturbances, should be taken into account when analyzing anisotropic fluxes of low-energy CRs as, e.g., for GLE on May 24–25, 1990 (Fedorov et al., 2002). The effect of the slight variations of model *B*, of both additive and multiplicative character, was examined in Bobik et al. (2001).

7.4.5 The Transmission Function at Middle Latitudes: Varying with IOPT

At middle latitudes, where the atmospheric cutoff for quiet geomagnetic conditions is negligible compared to the geomagnetic one, the magnetospheric transparency for CRs changes with the geomagnetic activity and with the local time of observations. Kudela and Usoskin (2004) have analyzed the structure of a TF for Lomnicky Štit in great detail for a wide range of parameters: calculations were performed for different local times with steps of 1 h as well as for six different levels of the geomagnetic activity characterized by parameter *IOPT* in the Tsyganenko-89 model. The variation of $R_{\rm C}$ and $R_{\rm U}$ depicts a wavy structure for each *IOPT* over a day with the maximum at 7–8 UT and minimum at 20–21 UT. The value of the cutoff rigidity decreases with increasing *IOPT* at all local times (Kudela et al., 1998). The TFs computed for different *IOPT* averaged over 24 h are displayed in Fig. 7.20.

The seasonal variability of cutoffs for Lomnicky Štit was found to be lower than the diurnal one (Kudela et al., 1998) and thus it is not considered here. One can see from Fig. 7.20 that the *TF* changes significantly with varying geomagnetic activity.

7.4.6 The Weighted Transmissivity Function

The weighted TF which accounts for the frequency of the occurrence of different level disturbances can be introduced as a reference for the long-term average geomagnetic activity. The probability of an occurrence of events with various *IOPT* is shown in the top panel of Fig. 7.21 for 1980–1990. The TF weighted over the probability of the occurrence of geomagnetic disturbances is shown in the bottom panel of Fig. 7.21.

Long-term averaged values of the vertical cutoffs for Lomnicky Štit, obtained through such weighted averaging (Fig. 7.21), are $R_{\rm L} = 3.466 \,\text{GV}$, $R_{\rm U} = 3.926 \,\text{GV}$, and $R_{\rm C} = 3.802 \,\text{GV}$. Although secular change of the geomagnetic field is small for the Lomnicky Štit location, the approach of the weighted TF should be considered with some caution if used for long-term studies of CRs, since the geomagnetic activity is changing with the solar cycle.

7.4.7 The Changing of the Transmissivity Function During Very Strong Geomagnetic Disturbance

In some cases, the time of observations should be taken into account. For instance, an increase in count rates of a number of middle- and low-latitude stations was observed during the morning hours associated with the very strong geomagnetic disturbance (K_p up to 9–) on March 31, 2001. However, high-latitude stations (Oulu and



Fig. 7.20 The TFs for Lomnicky Štit NM, 24-hour averaged, calculated using the Tsyganenko-89 model for different levels of geomagnetic activity (From Kudela and Usoskin, 2004)

Sanae) did not observe this increase. In order to understand this situation, Kudela and Usoskin (2004) estimated the expected NM response using Eq. 7.46 and the *TF* calculated for this particular time. The calculated change of the TF is so large (see Fig. 7.22) that an increase of the count rate expected at middle- and low-latitude stations is in accord with observations.

Kudela and Usoskin (2004) note that the Tsyganenko-89 model employs only a K_p index with a 3-h resolution with the upper bound of IOPT = 6. However, the profile of middle-latitude NM count rates corresponds to the measured D_{st} profile,



Fig. 7.21 *TOP* panel: probability of various *IOPT* occurring during the period 1980–1990 (histogram from data available at http://nssdc.gsfc.nasa.gov/omniweb). *Bottom* panel: the TF for Lomnicky Štit weighted by the probabilities displayed in the *top* panel (From Kudela and Usoskin, 2004)



Fig. 7.22 The TF *TF* for Lomnicky Štit at 06 UT with $D_{st} = -100$ nT (thin line) and $D_{st} = -358$ nT (corresponding to a minimum D_{st} on March 31, 2001, *IOPT* = 6, thick line) (From Kudela and Usoskin, 2004)

Table 7.3 Effective vertical cutoffs (in GV) for Lomnicky Štit in the Tsyganenko-89 field model and with D_{st} extension by the method of Tsyganenko (1989) added to IOPT = 6 (From Kudela and Usoskin, 2004)

UT		Magnetic activity						
	IOPT = 1	IOPT = 6	$D_{\rm st} = -100 nT$	$D_{\rm st} = -300nT$				
00	3.871	3.491	3.353	2.626				
06	3.892	3.691	3.564	2.981				
12	3.877	3.663	3.573	2.851				
18	3.860	3.532	3.329	2.563				

especially for those stations having asymptotics in the night sector (Kudela and Storini, 2002). The increasing D_{st} decreases significantly the rigidity cutoff and modifies the *TF* shifting it toward lower rigidities. The results of computations for two levels of D_{st} are shown in Table 7.3 and the TF affected by D_{st} is shown in Fig. 7.22.

7.4.8 Asymptotic Directions for a Middle-Latitude Station

The azimuthal and local time-dependence of CR intensity variations due to geomagnetic cutoff changes, especially at middle latitudes, were investigated in Flückiger et al. (1983), Kudo et al. (1987b), Flückiger et al. (1986). In the former of the cited papers, the vertical cutoff rigidities and their changes were determined by utilizing the trajectory-tracing technique in the magnetic field modeled as a simple dipole field to which the disturbance is superposed. Kudela and Usoskin (2004) have computed expected changes of asymptotic directions for various local times and geomagnetic activity levels using the Tsyganenko-89 field model. Figure 7.23 depicts the results for the low-rigidity part of the CR primaries contributing to the count rate of Lomnicky Štit NM. For the selected interval of rigidities, the computations show a rather stable structure where the neighboring asymptotic directions are smoothly organized. When the geomagnetic activity is low, only slight variations of the asymptotic longitude with the local time are expected, and the studied rigidity interval of 0.5 GV width corresponds to a wide longitudinal interval of asymptotes. An increase of the magnetic activity level leads, similarly to higher latitudes, to a westward shift and to shrinking of the asymptotic longitudinal extent. The asymptotes are shifted by more than 210° for 4 GV particles at midnight, when the activity is changed from IOPT = 1 to IOPT = 6 with $D_{st} = -300$ nT. The shifts are slightly smaller for the daytime observations. An experimental test of TF changes can be done either by NM latitude surveys or by measurements onboard low-altitude polar orbiting satellites. A real survey requires a long time during which the geomagnetic field can significantly change. However, a correlative analysis of data from NM located nearly at the same meridian over the entire range of latitudes and thus forming



Fig. 7.23 Asymptotic directions of 4.0-4.5 GV primary CR vertically accessing the Lomnicky Štit position at midnight and noon for different geomagnetic conditions The epoch for the internal field is January 21, 1986. The arrows correspond to asymptotic directions at 4.0 GV at each line (From Kudela and Usoskin, 2004)

a meridianal chain (e.g., Oulu – Kiel – Lomnicky Štit – Jungfraujoch – Rome – Athens – ESOI (Israel) – South Africa – Antarctica) would be also regarded as a latitude survey.

The latter approach has been recently performed in Smart and Shea (2001) using measurements of energetic solar protons on SAMPEX (Leske et al., 1997). It was concluded that more detailed dynamical models of the geomagnetic field are needed to obtain a better correspondence to space particle measurements. Leske et al. (2001) illustrated that measurements of solar particles onboard a low-altitude polar orbiting satellite, which provide an indication of the geomagnetic cutoff location four times per orbital period, are useful for possible warning of significant cutoff suppression. Most probably a single global parameter of magnetic activity adopted by models (like D_{st}) is not sufficient to explain the full details of observations.

7.4.9 Asymptotic Directions and Transmissivity Function for Low-Altitude Satellite Observations

A good possibility to experimentally study changes of the TF is provided by the SONG instruments onboard the low-altitude polar orbiting satellite CORONAS-I. The SONG measures, along with neutrons and gamma rays, protons with energy above 50 MeV (Balaz et al., 1994). Its high count rate allows studying variations of low-energy CR at different latitudes separately for each orbit, thus providing a nearly momentary latitudinal survey.

Kuznetsov et al. (2002) reported that, while being in agreement at high latitudes, SONG data did not correspond to the data of middle-latitude neutron monitors (Climax and LARC, both have $R_{\rm C} \approx 3 \,\rm GV$) during a strong geomagnetic disturbance and the related Forbush decrease on April 17, 1994. While NM did not record notable variations at middle latitudes, SONG observed a significant increase of CR at the same L values as Climax and LARC during the maximum D_{st} depression. Kudela and Usoskin (2004) have computed trajectories of CR for the location of the LARC station $(-62.20^{\circ}\text{S}, 301.04^{\circ}\text{E})$ both for the ground (altitude 20 km) and for a low orbit (500 km, corresponding to CORONAS-I). They found that a large $D_{\rm st}$ depression (-300 nT) may cause a very strong depression of the effective vertical cutoff rigidity from 3 GV down to 1.71 GV and to 0.92 GV for the altitudes of 20 km and 500 km, respectively. The computations were made with the rigidity step of 10^{-5} GV. The fine structure of the both penumbras is rather complicated. Narrow windows of allowed trajectories with stable asymptotic directions were found for the 500 km altitude. These windows correspond to particles entering the magnetosphere from the night side. Two samples of the penumbra are shown in Fig. 7.24. The interval of lower rigidities 0.86–0.87 GV (shown in the bottom panel of Fig. 7.24) has a very regular structure and the TF (equal to 1) in contrast to the other, more energetic, interval of 1.07–1.17 GV (upper panel). No such transparency windows were found for the altitude of 20 km. Such windows of transparency may result in the count rate increase observed at the satellite altitude, but missed by the ground NM.

The transparency window shown in Fig. 7.24 is narrow (0.01 GV in rigidity) and the effect of this window alone is rather small. However, this example stresses that the transmissivity of the magnetosphere for low-energy particles may be very different at different altitudes, even at the same geographical position, during periods of high geomagnetic activity. This indicates that a broader case study of the inconsistency between the "orbit-by-orbit profile" of a low-altitude satellite crossing the fixed middle-latitude *L*-shell and the ground-based NM profile at the same *L*(as, e.g., Fig. 3 in Kuznetsov et al. (2002) during geomagnetic disturbance and Forbush decrease) would be of interest from the point of view of penumbra expectations and approaches of the trajectory calculations.



Fig. 7.24 Fine structure of the penumbra at the altitude of 500 km above the position of LARC NM calculated using the Tsyganenko-89 model with D_{st} extension -300 nT. Rigidity intervals of 1.07–1.08 GV (*upper* panel) and 0.86–0.87 GV (lower panel) are depicted. The angular difference d α of two subsequent asymptotic directions is displayed by dots (labeled *left* axis, in degrees, similar values as in Fig. 7.18). Solid line and the *right* axis in the *upper* panel correspond to the computed TF (in units 0.1%). The TF = 1 for the lower panel (From Kudela and Usoskin, 2004)

7.4.10 Main Results and Discussion

Using the method of trajectory computations of CRs in the Tsyganenko-89 model of the geomagnetic field, with the self-adjusted control of the elementary computational step by keeping the "smoothness" of the trajectory, Kudela and Usoskin (2004) studied details of the geomagnetic cutoff penumbra for two CR stations: middle-latitude Lomnicky Štit and high-latitude Oulu. The complicated structure of the penumbra, computed with high rigidity resolution, implies that intervals of smooth change of asymptotic directions with rigidity correspond mainly to trajectories entering the dayside magnetopause, while the night entry is sometimes seen as chaotic changes of the asymptotic directions. The asymptotic directions on the nightside are influenced by variations of B_z in the neutral sheet of the geomagnetic tail. The changes of the cutoff and narrowing of the asymptotic range with the magnetic activity and local time should be taken into account for the

study of low-energy CR anisotropy in interplanetary space or of the anisotropy of solar energetic particles during GLE for high-latitude stations.

The TF, accounting variability of the magnetic field with changing K_p and with local time, may be used as an additional reference (to the R_L , R_C , R_U concept) to describe the average magnetospheric transparency at middle latitudes. It was found that the structure of the penumbra and the corresponding TF can be significantly different for the ground-based observations and for low-altitude polar orbiting satellites during strong geomagnetic disturbances. As Kudela and Usoskin (2004) have qualitatively shown, this effect can be responsible for the observed difference between CR intensity as measured by ground-based stations and by low-altitude polar orbiting satellites. A correlative study of data from a group of NM (meridian chain) and low-altitude polar satellites with large geometrical factors for high-energy particles would provide a tool for testing the transparency expectations based on computations of trajectories.

7.5 Geomagnetic Cutoff Variations Observed by Tibet NM During the Maximum of Solar Activity: Checking Within the Frame of the Tsyganenko-89 Model

7.5.1 Tibet NM and Observation Data for Magnetic Storm Events

According to Miyasaka et al. (2003), during the strong geomagnetic disturbance on March 31, 2001, several NM including the Tibet NM have observed specific time variations of CR intensity. The low- and middle-latitude (high and medium CR cutoff rigidity) NM stations observed a clear intensity increase while the highlatitude (low cutoff rigidity) stations observed a continuous decrease after the onset of the magnetic storm.

Tibet NM station was started as a part of the Japan–China international CR observation program on September 1998 (Kohno et al., 1999; Miyasaka et al., 2001). The stable continuous data gathering started in October 1998 and has worked through the solar maximum phase. The location of the Tibet NM station is at Yangbajing International Cosmic Ray Observatory (30.11° N, 90.53° E, 4,300 m above sea level, cutoff rigidity 14.1 GV). The observation system consists of 28 NM-64 neutron counters and records the single counts and multiplicity 1–8 from each two adjacent counters and thus this station performed at a highest counts rate (1.07×10^7 counts per hour) with high geomagnetic cutoff and high time resolution.

Panel a in Fig. 7.25 shows the CR intensity increase coincident with the geomagnetic disturbance (peak $D_{st} = -321 \text{ nT}$) that occurred on April 7, 2000.

One of the largest geomagnetic disturbances since Tibet NM station started has occurred on March 31, 2001 (peak $D_{st} = -358 \text{ nT}$ at 8 UT). During this geomagnetic disturbance a CR intensity increase was observed in coincidence with the D_{st} decreases shown in panel b of Fig. 7.25.



Fig. 7.25 CR intensity variations (in %) observed at Tibet NM and D_{st} values (in nT) are shown for the magnetic storm events of April 7, 2000 (panel **a**) and March 31, 2001 **b** (From Miyasaka et al., 2003)



Fig. 7.26 The same as in Fig. 7.5.1, but for magnetic storm events at July 15, 2000 (panel **a**) and April 11, 2001 **b**. From Miyasaka et al., (2003)

Contrary to these CR intensity increases, there are also the CR intensity decreases observed during the geomagnetic disturbances. Panels a and b in Fig. 7.26 show these decrease events which occurred on July 15, 2000 (peak $D_{st} = -300$ nT) and April 11, 2001 (peak $D_{st} = -256$ nT).

Table 7.4 lists the $\Delta N/N_0$ of CR intensity (in %) during the large geomagnetic disturbances (with $|D_{st}| > 200 \text{ nT}$). The $\Delta N/N_0$ CR intensity variation is simply estimated by taking the difference between the CR intensity of geomagnetic storm onset and peak time.

August 12, 2000

March 31, 2001

November 6, 2001

November 24, 2001

April 11, 2001

 $\frac{\text{Date Peak } |D_{st}| \text{ (nT) } \text{CR } \Delta N/N_0(\%)}{\text{October 22, 1999} -237 2.27}$ April 7, 2000 -321 2.28
July 15, 2000 -300 -0.38

-237

-358

-256

-277

-213

1.62

2.12

2.69

-0.62

-0.84

Table 7.4 List of geomagnetic disturbances with $|D_{st}| > 200 \text{ nT}$ during the period January 1999 to December 2002. The size of CR intensity variation $\Delta N/N_0$ (in %) during the magnetic disturbances are also shown (From Miyasaka et al., 2003)

Miyasaka et al. (2003) noted that the CR intensity increase event is relatively a coincidence to the peak intensity time and the minimum D_{st} time but the CR intensity decrease event delays the minimum intensity from minimum D_{st} time.

7.5.2 Analysis of Data and Comparison with the Tsyganenko-89 Model

The CR intensity increase during the geomagnetic disturbance is thought to be a result of cutoff rigidity decreasing, and lower rigidity particles were observed. The CR incident asymptotic directions are oriented to the nightside of the magnetosphere and thus the ring current evolution increased the magnetospheric transparency in the tail. To examine this feature, Miyasaka et al. (2003) estimated the geomagnetic cutoff rigidity from particle trajectory computations. The geomagnetic field for this computation was adapted from the Tsyganenko-89 model (Tsyganenko, 1989 see Section 7.1) with an extension of the D_{st} parameter according to Boberg et al. (1995). This model has been modified to use D_{st} for the effective ring current field parameter as follows:

$$C_5(D_{\rm st}) = -10220 + 408.5D_{\rm st}.$$
(7.47)

From the particle trajectory simulation using the modified Tsyganenko-89 model, Miyasaka et al. (2003) estimated the cutoff rigidity variation for the Tibet NM station during March 31–April 1, 2001. The result is shown in Fig. 7.27 with observed CR intensity variations (in %). Figure 7.27 shows a relatively good correspondence of the Tibet NM observed CR intensity variation time-profile with expected cutoff rigidity time-variation. Using the coupling function from Dorman et al. (2000), the cutoff rigidity variation in Fig. 7.27 indicated the expected CR intensity increase of 2.4%, which is almost consistent with the observed peaked value (Miyasaka et al., 2003). This result indicates the short-term changes of the geomagnetic CR cut-off rigidity that occurred at the geomagnetic disturbance and the D_{st} value improves



Fig. 7.27 Cutoff rigidity variation during March 31–April 1, 2001 which was estimated from the Tsyganenko-89 model with the D_{st} extension (see Eq. 7.47) are shown. Hourly data of CR intensity variation (in %) observed at Tibet NM are also shown (From Miyasaka et al., 2003)

the picture of cutoffs during high activity periods. Since cutoff rigidity decreases during geomagnetic disturbance, it is not possible to simply explain the CR intensity decrease events of July 15, 2000 and April 11, 2001 as shown in Fig. 7.26. These CR intensity decrease events occurred during the Forbush-decrease phase so this may be thought of as cutoff rigidity that may decrease with the geomagnetic disturbance but the interplanetary source CR intensity has decreased with an IMF disturbance much bigger, and thus the Tibet NM cannot observe a CR intensity increase (this type of CR events was considered in detail in Dorman, M1963a, b, M1975b).

7.6 Magnetospheric Effects in CR During the Magnetic Storm in November 2003

7.6.1 The Matter of Problem

CR variations due to changes in the magnetosphere are evaluated in Belov et al. (2005) for the severe magnetic storm on November 20, 2003 using data from the worldwide NM network and the global survey method (see for details in Chapter 3 of Dorman, M2004). From these results, the changes in the planetary distribution of magnetic cutoff rigidities during this disturbed period were obtained in dependence of latitude. A correlation between the D_{st} index and cutoff rigidity

variations was defined for each CR station. The maximum changes in cutoff rigidities occurred while the D_{st} index was around $-472 \,\text{nT}$. The geomagnetic effect in CR intensity reached 6-8% at some stations, and it seems to be the greatest one recorded during the history of NM observations. The latitudinal distribution shows a maximum change at geomagnetic cutoff rigidities around 7-8 GV. This corresponds to unusually low latitudes for maximal effect. Cutoff rigidity variations were also calculated utilizing the Tsyganenko-89 model and its development (Tsyganenko, 1989, 2002a, b; Tsyganenko et al., 2003; see also Section 7.1) for a very disturbed magnetosphere. A comparison between experimental and modeling results revealed a big discrepancy in cutoff rigidities of less than 6 GV. The results on the geomagnetic effect in CR can be used for validating magnetospheric field models during very severe storms. Disturbances in the earth's magnetic field during magnetic storms can cause essential changes in the charged particle trajectories in the magnetosphere, sometimes to such an extent that allowed trajectories become forbidden, and conversely. This has two main consequences for ground-level observations: (1) the effective cutoff thresholds change; (2) the effective asymptotic directions of the particles and thus the reception coefficients for different stations also change. Both of these consequences are important for solar CRs, whereas for galactic CRs, the first effect usually dominates. The magnetosphere effect associated with the cutoff rigidity changes may be great enough to distort essentially a CR variation at the fixed NM station or even to change its behavior completely. An example of such a great magnetosphere effect during the storm on November 20, 2003 is presented in Fig. 7.28.

According to Belov et al. (2005), there are several reasons for the special interest in the CR magnetosphere variations. First, these effects are interesting from a physical viewpoint: creation, evolution, and decay of the magnetosphere current systems, global interaction of cosmic radiation with the geomagnetic field. Analysis of the CR geomagnetic effects makes it possible to carry out independent validation of current system models in all phases of magnetic storms. At the beginning of a magnetic storm, usually associated with the magnetopause current systems, cutoff rigidity R_C increases relatively to the quiet level, whereas R_C decreases significantly during the main phase of geomagnetic storm. The latitudinal and longitudinal dependences of these effects reveal themselves in different ways (Fluckiger et al., 1981, 1987; Baisultanova et al., 1995) during the magnetic storm. The cutoff rigidity variations caused by the magnetosphere current ring during the main phase of the storm, have an insignificant longitudinal dependence because of the ring symmetry. On the contrary, during the initial phase of the magnetic storm, they have a significant longitudinal dependence, since current daytime distribution of the magnetosphere differs considerably from the night distribution.

Second, the study of the magnetosphere effect is important from the methodological point of view, since these effects hinder the discrimination of the primary CR variations and should be excluded from the initial data. Large magnetosphere effects are usually observed simultaneously with big modulation effects in CRs since they are both caused by solar and interplanetary activity. CR variations due to cutoff rigidity changes during a big magnetic storm have already been studied



Fig. 7.28 Uncorrected (*upper* panel) and corrected (lower panel) for the magnetospheric effect CR variations at the stations Athens (Athn), Potchefstroom (Ptfm), Santiago (Sntg), Apatity (Apty), and McMurdo (Mcmd) during the storm on November 20, 2003. Santiago corrected for the magnetospheric effect is not plotted in the lower panel to avoid picture overloading (From Belov et al., 2005)

in many papers (Debrunner et al., 1979; Baisultanova et al., 1987, 1995; Sdobnov et al., 2002). Nevertheless, several important problems still remain to be solved. They include the following:

- 1. To study all large ($D_{st} < -100 \,\text{nT}$) magnetic storms and thereby develop a method of correction for the geomagnetic effect in CR data from the worldwide neutron monitor network. It is expected to define a quantitative relation between D_{st} and possible ΔR_C for each station after the analysis of a sufficient number of magnetic storms.
- 2. To compare the current system models and experimentally derived changes in cutoff rigidities at different stages of the magnetic storm. In this analysis, direct incorporation of CR data is important in order to study the global effect of the current systems on particle trajectories. This is both during the initial phase of the magnetic storm, associated with currents in the magnetopause, and during the main phase, when cutoff rigidity is significantly reduced.

7.6.2 Solar and Interplanetary Activity in November 2003

Two sunspot groups were particularly active on November 18, 2003: 501 (484 in previous rotation) and 508 (486). The last big flare in the group 508, accompanied by a powerful coronal mass ejection (CME), was observed on November 18 at the eastern limb (M4, onset at 09.23 UT, maximum at 10.11 UT). At the same time in group 501 two long-duration flares occurred in the center of the disk (M3.2/2N N00E18, onset at 07.16 UT, maximum at 07.54 UT; M3.9, onset at 08.12 UT, maximum at 08.31 UT), which were also followed by powerful and extremely effective CMEs. The severe magnetic storm associated with the flares on November 18 (at least with the two central flares and possibly with all three) started on November 20. After a shock arrival at 07.28 UT (data from SOHO) and corresponding SSC at 08.04 UT, when the earth ran into a long magnetic cloud, the IMF intensity reached 60 nT, and its negative B_Z component had almost the same value. Consequently, geomagnetic activity at the end of November 20 increased up to the level of a severe magnetic storm and the $D_{\rm st}$ index fell to $-472\,{\rm nT}$, it was lower only on one occasion on March 13–14, 1989. Red aurora was observed, even in southern Europe (Athens, http://www.perseus.gr/Astro-Aurorae-20031120-001.htm).

7.6.3 Data and Method of Analysis

In Belov et al. (2005) hourly data from 46 NM of the worldwide network have been employed in a detailed analysis: 19 high-latitude ($R_C < 1.2 \text{ GV}$), 22 middle- and low-latitude, and 5 subequatorial ($R_C > 10 \text{ GV}$) stations. D_{st} index for November 2003 was taken from http://swdcwww.kugi.kyoto-u.ac.jp/ dstdir/(WDC-C2).

The global survey method (GSM) which is conceptually a version of spherical analysis (Krymsky et al., 1966; Belov et al., 1983, 1999; see details in Dorman, M1974, and Chapter 3 in Dorman, M2004) has been utilized for calculations. This method allows a set of parameters defining the galactic CR density and anisotropy to be derived from the ground-level NM network. The method takes into account the CR transformation in the magnetosphere and atmosphere and uses trajectory calculations in the earth's magnetic field and the NM response (coupling) functions (Dorman, M1957, M1963a, b, M1975a, M2004). Different versions of this method have been evolved and improved at different stages of data processing. Belov et al. (2005) used as a basis the version described by Belov et al. (1983) and Baisultanova et al. (1987, 1995).

In general, the observed CR variations at each neutron monitor *i* consist of the following components:

$$\Delta N_i / N_{io} = \delta_{i,izotr} + \delta_{i,anizo} + \delta_{i,error}, \qquad (7.48)$$

where $\delta_{i,izotr}$ and $\delta_{i,anizo}$ mean isotropic and anisotropic CR variations out of the magnetosphere and $\delta_{i,error}$ is residual dispersion related to possible apparatus

7 Magnetospheric Models and their Checking by Cosmic Rays

variations and inadequate utilization of a model. On the assumption of only the first spherical harmonic of CR anisotropy (which is true in the majority of events), the variation in the counting rate of NM at point *i* with rigidity R_{ci} located at level h_i may be described by the equation:

$$\frac{\Delta N_i}{N_{io}} = \int\limits_{R_{ci}}^{\infty} \frac{\Delta D(R)}{D_o(R)} W_i(R, R_{ci}, h_i) dR + (C_{ix}a_x + C_{iy}a_y + C_{iz}a_z) + \delta_{i, \text{resid}}, \quad (7.49)$$

where

$$\frac{\Delta D(R)}{D_o(R)} = a_o R^{-\gamma} \tag{7.50}$$

is a rigidity dependence of the galactic CR density variations, a_o is the magnitude of CR density variation (zero harmonic of CR variations), a_x , a_y , a_z are three components of the first harmonic of CR anisotropy; C_{ix} , C_{iy} , C_{iz} are the coupling coefficients for each component respectively taken from Yasue et al., (M1982); $W_i(R, R_{ci}, h_i)$ is the response (coupling) function for detector, located at the level h_i at the point with geomagnetic cutoff rigidity R_{ci} ; $\delta_{i,resid}$ is residual discrepancy. In Eq. 7.49 the first member (integral) describes the isotropic part and the second one describes the anisotropic components of the CR variations.

The system from *n* equations (*n* is the number of NM) was solved by the leastsquares method relative to the unknown parameters a_o and γ in Eq. 7.50 and unknown components of anisotropy a_x , a_y , a_z in Eq. 7.49. This model has been verified in a large number of cases and usually gives a proper fit to the experimental data. It would be reasonable to include in the model described by Eq. 7.49 a detailed description of the magnetosphere part of the CR variations. This approach was utilized by Dvornikov and Sdobnov (2002) where they specify the model dependence ΔR_{ci} on the rigidity R_{ci} as

$$\Delta R_{ci} = \left(b_1 R_{ci} + b_2 R_{ci}^2\right) \exp\left(-R_{ci}^{1/2}\right).$$
(7.51)

In this case, the system solves the set of parameters b_1 , b_2 , and a_o , γ , a_x , a_y , a_z . This method has some advantages, but unfortunately, the assignment of a dependence ΔR_{ci} on the rigidity R_{ci} in this approach limits in advance the form of derived latitudinal ΔR_{ci} distribution. Also, introducing the additional unknown parameters makes the solution more unstable.

In the approach of Belov et al. (2005), authors work separately with the residual discrepancies. Utilizing the model, described by Eq. 7.49, during strong magnetospheric disturbances, they used a two-step method for the calculations, the so called BDY-method described in Belov et al. (1983) and widely used in Section 6.24). The CR variation due to the magnetospheric effect, according to Dorman (M1957, M1975b, M2004), may be written as

$$\delta_{i,\text{mag}} = -\Delta R_{\text{c}i} W_i \left(R_{\text{c}i}, R_{\text{c}i}, h_i \right) \left(1 + \frac{\Delta D \left(R_{\text{c}i} \right)}{D_o \left(R_{\text{c}i} \right)} \right).$$
(7.52)

Since the $W_i(R_{ci}, R_{ci}, h_i)$ value is small for low R_{ci} , the magnetospheric CR density variation could be disregarded for high-latitude stations. The first step is to solve the set of Eq. 7.6.2 for 19 high-latitude NM. The next step is to use the found parameters and correct the middle and low-latitude NM data (27 stations) for the extraterrestrial variations. The discrepancies are assumed to arise from the geomagnetic effect. The Belov et al. (2005) approach is based directly on this difference between the model and experimental data during periods of a distorted magnetosphere. According to this, one can write:

$$\delta_{i,\text{resid}} = -\Delta R_{\text{c}i} W_i \left(R_{\text{c}i}, R_{\text{c}i}, h_i \right) \left(1 + \frac{\Delta D\left(R_{\text{c}i} \right)}{D_o\left(R_{\text{c}i} \right)} \right) + \delta_{i,\text{ mod }} + \delta_{i,H} + \delta_{i,L}, \quad (7.53)$$

where $\delta_{i, \text{mod}}$ is the contribution to dispersion of non-adequacy of the CR variation model (form of rigidity spectrum, effect of higher-order harmonics), $\delta_{i,H}$ is the error due to statistical accuracy of the data, and $\delta_{i,L}$ is the low-frequency component due to possible apparatus drift. It is possible to minimize the contribution from the last two terms, paying particular attention to the quality of the employed data (correction for the drifts and meteorological effect, selection of stations with good data). We cannot completely avoid a contribution from $\delta_{i, \text{mod}}$ due to a possible second harmonic or more complicated spectrum. However, this part of the dispersion would not have a certain longitudinal or latitudinal distribution which is characteristic for geomagnetic effects. So, we can consider the three last members in Eq. 7.53 to be negligible compared with magnetospheric variations, and then from Eq. 7.53 follows

$$\delta_{i,\text{resid}} \approx \delta_{i,\text{mag}},$$
 (7.54)

i.e., all residual errors may be attributed to the magnetosphere effect. In this case, taking into account Eq. 7.52 we can write:

$$\Delta R_{ci} = -\delta_{i,resid} / W_i(R_{ci}, R_{ci}, h_i) \left(1 + \frac{\Delta D(R_{ci})}{D_o(R_{ci})} \right).$$
(7.55)

In such a way, the planetary distribution of the geomagnetic cutoff rigidity variations can be found, and ΔR_{ci} values at different points are determined independently of each other. This determination is absolutely irrelevant to the model concepts concerning the latitude and longitude distribution of the magnetic storm effects.

7.6.4 Uncorrected and Corrected for the Magnetospheric Effect CR Variations

Uncorrected (upper panel) and corrected (lower panel) for the magnetospheric effect CR variations at the Athens, Potchefstroom, and Santiago stations are presented above in Fig. 7.28. They are compared with the same variations at high-latitude stations Apatity and McMurdo. Data from different NM indicate that

the Forbush decrease was moderate despite the extremely severe magnetic storm $(D_{st} = -472 \text{ nT})$ in this period. The magnetospheric effect in CR was maximal at the relatively low latitude, but not at the middle-latitude stations, as it is often observed. It was so significant by the amplitude (6–8%) that the Forbush decrease at the Athens, Potchefstroom, and other low-latitude stations was completely masked.

7.6.5 Cutoff Rigidity Variations During the Magnetic Storm

Cutoff rigidity variations ΔR_{ci} were calculated for each station throughout the storm by the above-mentioned BDY-method. This result is plotted for Athens and Jungfraujoch stations in Fig. 7.29, and for all other stations – in Fig. 7.30.

7.6.6 Correlation of the Obtained ΔR_{ci} with D_{st} Index

Comparison of the obtained ΔR_{ci} with D_{st} index reveals a very high correlation over the whole period under consideration. Although the Jungfraujoch station is usually two times more sensitive to geomagnetic effects than the station in Athens (see below), in this case Athens recorded a geomagnetic effect twice larger than Jungfraujoch. As shown below, such an effect is caused by the peculiarity of the storm on November 20, 2003, namely, by the specific space distribution of the current system. Regression dependence between ΔR_{ci} with D_{st} for the same stations



Fig. 7.29 Derived variations of the cutoff rigidity ΔR_{ci} and D_{st} index at the stations Athens (Athn) and Jungfraujoch (Jung) during the severe magnetic storm on November 2003 (From Belov et al., 2005)



Fig. 7.30 Correlation of the cutoff rigidity variations ΔR_{ci} at different stations and D_{st} index during the period November 19–24, 2003 (From Belov et al., 2005)

is plotted in Fig. 7.31 (for some other stations these dependences are collected in Fig. 7.32). Two regions are clearly pronounced in Figs. 7.31 and 7.32: one with a small ($D_{st} > -50 \text{ nT}$) and another with a large ($D_{st} < -50 \text{ nT}$) D_{st} index. Within the first region an accuracy of ΔR_{ci} can be estimated as ~0.1 GV for each station. Within the region of large D_{st} index an approximately linear dependence ΔR_{ci} on D_{st} is observed:

$$\Delta R_{\rm c} = k \left(D_{\rm st} + 50 \right). \tag{7.56}$$

Figure 7.31 shows that for the Athens NM the regression coefficient k is equal to 0.0027 GV/nT, whereas for Jungfraujoch it is 0.0018 GV/nT.

Figure 7.32 shows that really about for all NM within the region of large D_{st} index, an approximately linear dependence ΔR_c on D_{st} is observed. The regression coefficient *k* mostly varied in about 2–3 times from k = 0.00267 GV/nT for Athens



Fig. 7.31 Example of regression diagrams as evidence of the high correlation between the cutoff rigidity variations ΔR_{ci} and D_{st} index (determined by Eq. 7.56) for the two stations (Athens and Junfraujoch) during the magnetic storm in November, 2003 (From Belov et al., 2005)



Fig. 7.32 The same as in Fig. 7.31, but for other NM (From Belov et al., 2005)

and $k = 0.00289 \,\text{GV/nT}$ for Potchefstrum to $k = 0.00111 \,\text{V/nT}$ for Haleakala. The exclusion shows only Moscow NM with very small $k = 0.00022 \,\text{GV/nT}$, about 5–10 times smaller than other NM. Why did the regression coefficient k in Eq. 7.6.9 vary so much? The explanation for this strange phenomenon may be found in careful

investigation of magnetosphere models including ring current (main cause of D_{st} variation) and their influence on planetary distribution of cutoff rigidity changes during great magnetic disturbances.

7.6.7 Latitudinal Dependences of Cutoff Rigidity Variations

The latitudinal dependences of cutoff rigidity variations were defined as ΔR_c distribution by the R_c for each hour starting from the shock arrival and up to final recovery of the magnetosphere. These results are presented in Fig. 7.33.



Fig. 7.33 Cutoff rigidity variations ΔR_c versus R_c at different instants throughout the magnetic storm on November 20–21, 2003. Cutoff rigidity R_c are taken for a quiescent magnetosphere and determined by the main magnetic field model IGRF-1995 (Smart and Shea, 2003) (From Belov et al., 2005)

7.6.8 Comparison of Cutoff Rigidity Variations Determined by CR Data and Derived from Magnetosphere Models by Trajectory Calculations

For certain points of this magnetic storm, an attempt was made to compare the "experimental" results derived by the above-mentioned method with the calculations from the model for a distorted magnetosphere. The "experimental" cutoff rigidity variations ΔR_c (dots) and ΔR_c calculated from the storm magnetosphere model (triangles) of Tsyganenko (2002a, b) versus cutoff rigidity R_c (for a quiescent magnetosphere in the epoch 1995) are illustrated in Fig. 7.34 for the hours before, at the peak, and after, the storm peak.

Calculations for Fig. 7.34 were performed in Belov et al. (2005) utilizing the latest Tsyganenko model T01S for a stormed magnetosphere by the Pchelkin and



Fig. 7.34 Cutoff rigidity variations (ΔR_c) versus the cutoff rigidities (R_c) (which proves latitudinal distribution) for different instants of the November 20, 2003 geomagnetic storm: before the main phase of the storm (12:30 UT), during the peak phase (19:30 UT), 1 h later peak phase of the storm (20:30 UT), and 4 h later (23:30 UT). Dots mark the points derived from CR experimental data by the global survey method with their errors, triangles correspond to ΔR_c calculated by the "storm" model (T01S) of Tsyganenko (2002a,b). Cutoff rigidities R_c (along the abscissa) are determined by the main magnetic field model IGRF-1995 (Smart and Shea, 2003). Solid and dashed lines illustrate an interpolation throughout the experimental and model points correspondingly and light lines interpolate the model points for rigidities more than 6 GV (From Belov et al., 2005)

Vashenvuk (2001) method. The particle trajectories were calculated from the main cone to the Störmer cone adding all allowed intervals (i.e., for the flat spectrum of CRs). The step of calculations was 0.002 GV. The time for the trajectory calculations for quasi-trapped particles was chosen so as to reach the vicinity of the asymptotic value. The model was tested for the rather quiet period at 06.30 UT on November 20, 2003. For this point, the classical package for the Tsyganenko-89 model (see Section 7.1) and the new T01S model give very close values. Cutoff rigidity variations ΔR_c were determined relative to this moment of the quiescent magnetosphere. Since experimental points have been derived for the R_c determined by the main magnetic field model IGRF-1995 (Shea and Smart, 2001) they may be shifted along the abscissa by 0.1-0.2 GV relative to those calculated from the Tsyganenko model. One can see that there is good agreement between experimental (obtained from CR data) and calculated values for rigidities >6 GV, moreover, without any normalization. However, we see a sharp discrepancy at rigidities of less than 6 GV. Possibly, the model T01S still is not adequate for the greatest magnetosphere disturbances and this causes a discrepancy at lower rigidities. Using the above-described "experimental" method, the same analysis was performed for other magnetic storms of less magnitude, and the classical latitudinal dependence of $R_{\rm c}$ changes with maximum at 3–4 GV was obtained (Baisultanova et al., 1987, 1995; see Chapter6, this volume).

7.6.9 On the Consistency of the "Storm" Models with the Current Distribution Derived from Spacecraft Data

Maltsev and Ostapenko (2004) analyzed the consistency of the existing "storm" models with the experimentally derived current distribution based on large sets of spacecraft data. In Fig. 7.35, adopted from this paper, the azimuthal diagrams of the electric currents flowing in the magnetosphere are presented as plotted by experimental data and as calculated statistically from different models. The currents were extracted from the magnetic databases of Fairfield et al. (1994) for $D_{\rm st} = -70\,{\rm nT}$ and from Tsyganenko (2002a, b) for $D_{st} = -140 \,\text{nT}$ (this procedure is described in detail by Maltsev and Ostapenko (2004). Several models of the magnetic field in the magnetosphere have been used to calculate current flows for the same $D_{\rm st}$ (Tsyganenko, 2002a, b;Tsyganenko et al., 2003; Alexeev et al., 2001, 2003; Maltsev and Ostapenko, 2001, 2004). A comparison of the model and experimental measurements shows fairly good agreement for a moderately disturbed magnetosphere while $D_{\rm st} = -70\,{\rm nT}$ (Maltsev and Ostapenko, 2004, model), but no model adequately reflects the real distribution of the current flows in a very disturbed magnetosphere, even under $D_{st} = -140 \,\mathrm{nT}$, not to mention a lower D_{st} . In particular these models are not adequate for calculations of $\Delta R_{\rm c}$ during giant magnetic storms with $D_{\rm st}$ amplitude of several hundreds nT as occurred on November 20, 2003.



Fig. 7.35 Azimuthal currents in the magnetosphere statistically extracted from the magnetic databases (Maltsev and Ostapenko, 2004), *left* column; comparing with model currents calculated from various models (other panels) for two levels of the magnetospheric storm: $D_{\rm st} = -70$ nT and $D_{\rm st} = -140$ nT (From Belov et al., 2005)

7.6.10 On the Specific Feature of the November 2003 Event and on the Radius of the Ring Current

As already mentioned, a specific feature of this event is that maximal magnetosphere effect in CR was recorded at low-latitude stations, instead of at middle-latitude as is usually the case. On this occasion the maximum in the latitudinal distribution of the cutoff rigidity variations is shifted significantly to the bigger rigidity and is around 8–9 GV (instead of the usual 3–5 GV). This means that the ring current, which, according to the simplest model (Treiman, 1953) is distributed by latitude proportionally to cosines of this latitude, flows maximally close to the earth in this case and is located at $3r_E$ from the earth's center. In magnetic storms when the maximum in latitudinal distribution of the cutoff rigidity variations is nearly 3–5 GV, the current system is placed at a geocentric distance of ~5 r_E .

7.6.11 On Possible Errors in Obtained Results

The errors given in Fig. 7.34 are those derived from the system equation solution for the quiet period and caused by the statistical accuracy of observations at each point. In fact, the errors may be caused by some other sources which are more difficult to estimate. In particular, we do not know the exact response function around the geomagnetic cutoff rigidity for each station. The response (coupling) functions from Clem and Dorman (2000) are presented for several stations in Fig. 7.36.



Fig. 7.36 Response (coupling) functions of the CR neutron component for several CR stations (From Belov et al., 2005)

Penumbra region, as well as inclined incident particles, lead to a blur and uncertainty in the response function near the R_c ; hence, some effective values have to be used to account properly for this blur. The observed dispersion of ΔR_c in Fig. 7.34 seems to be related partly to this uncertainty and sometimes to the difference between the dayside and nightside magnetosphere at the points of observation (longitudinal effect).

7.6.12 On the Sensitivity of NM to CR Magnetospheric Variation

Since the magnetospheric variation in CRs is defined as the product $\Delta R_{ci}W_i$ (R_{ci}, R_{ci}, h_i) , the value of the response (coupling) function $W_i(R_{ci}, R_{ci}, h_i)$ near the cutoff rigidity R_{ci} indicates station sensitivity to the magnetosphere effect. A list of the stations most sensitive to the geomagnetic effect, together with their characteristics (geographic coordinates, altitude, standard atmospheric pressure, and cutoff rigidity for the epoch 1995) is presented in Table 7.5.

In the last column of Table 7.5, the sensitivities as the values of $W_i(R_{ci}, R_{ci}, h_i)$ are given for the quiet magnetosphere in %/GV units. It means that if ΔR_{ci} at all stations are the same and not too big, the magnetosphere CR density variations will be proportional to this value. As seen from Table 7.5 the Jungfraujoch station is

Station	Short	Geog	r. coord.	Alt.	h _O	R _C	Wi
Name	name	Lat.	Long.	(m)	(mb)	(GV)	$(\% GV^{-1})$
Jungfraujoch	JUNG	46.55°	7.98°	3,550	643	4.48	10.62
Irkutsk-3	IRK3	52.28	104.02	3,000	715	3.66	9.49
Climax	CLMX	39.37	-106.18	3,400	685	3.03	9.36
Alma Ata-B	AATB	43.14	76.60	3,340	675	6.69	9.10
Yerevan-3	ERV3	40.50	44.17	3,200	700	7.60	8.33
Irkutsk-2	IRK2	52.28	104.02	2,000	800	3.66	8.29
Yerevan	ERVN	40.50	44.17	2,000	800	7.60	7.36
Potchefstroom	PTFM	-26.68	27.92	1,351	869	7.30	6.82
Mexico	MXCO	19.33	-99.18	2,274	794	9.53	6.59
ESO (Israel)	ESOI	33.30	35.78	2,055	800	10.00	6.37
Alma Ata-A	AATA	43.25	76.92	806	938	6.66	6.36
Irkutsk	IRKT	52.10	104.00	433	965	3.66	6.18
Tibet	TIBT	30.11	90.53	4300	606	14.10	6.12
Tsumeb	TSMB	-19.20	17.60	1240	880	9.29	6.00
Hermanus	HRMS	-34.42	19.22	26	1013	4.90	5.89
Huancayo	HUAN	-12.03	-75.33	3400	704	13.45	5.79
Rome	ROME	41.90	12.50	60	1009	6.32	5.75
Haleakala	HLEA	20.72	-156.27	3052	724	12.91	5.72
Athens	ATHN	37.93	3.72	40	980	8.53	5.22
Beijing	BJNG	40.04	116.19	48	1000	9.56	5.01
Santiago	SNTG	-33.48	-70.71	560	960	11.00	4.71

Table 7.5 List of NM, most sensitive to magnetospheric effects (From Belov et al., 2005)

approximately twice as sensitive to magnetospheric effect as Athens. At the same time, high-latitude stations with low cutoff rigidity possess very low sensitivity. They practically never respond to geomagnetic disturbance and do not show any effect on CRs at this time. A different effect in CR variations at different stations during magnetic storms characterizes R_c changes and the peculiarity of the ΔR_c planetary distribution during this storm. Thus, in the event of November 20, 2003, Athens NM showed a magnetospheric effect double the size of that shown by the Jungfraujoch. This is related to the particular latitudinal distribution of the cutoff rigidity variations during this event.

7.6.13 Summary of Main Results

From the above analysis, Belov et al. (2005) conclude the following:

- 1. At the beginning of the extreme magnetic storm on November 20, 2003 a small magnetospheric effect in CR was recorded, whereas an exclusively large effect was observed during the main phase of this storm.
- 2. The global survey method applied to the CR data from the worldwide NM network allowed the latitudinal distribution of the cutoff rigidity variations to be obtained for each hour during the main and recovery phases of this magnetospheric storm. These results may be employed in analyzing the dynamics of the evolution and damping out of the ring current systems.
- 3. During the magnetic storm on November 20, 2003, the ring-current system was located at a closer geocentric distance ($\sim 3r_E$) than is usually observed. As a consequence, the maximal magnetospheric effect in CRs was recorded at lower latitudes but not at the usual middle-latitude stations. Owing to this anomaly the maximum changes of the geomagnetic cutoff rigidity were shifted from the usual value of 3–5 GV to 7–8 GV.
- 4. The calculations of the cutoff rigidity changes performed utilizing the "storm" model T01S of the magnetosphere magnetic field, show good agreement between experimental and modeling values for rigidities >6 GV and great discrepancy for the lower rigidities. One reason for this may be that the "storm" model is not yet an adequate description of the real magnetosphere during the greatest disturbances.

7.7 On Checking the Magnetosphere Models by Galactic CRs: The Great Magnetic Storm in November 2003

7.7.1 The Matter of Problem

Magnetic fields in the earth's magnetosphere change in response to solar-wind disturbances. Dynamic processes in the magnetosphere lead to variations in CR cutoff rigidity and CR asymptotic directions that results in changes CR fluxes into the magnetosphere and on the earth's surface. Thus magnetospheric CR effects reflect exciting, developing, and decaying of current systems in the magnetosphere and they can be used as an independent information source for additional testing of magnetosphere models. Magnetospheric CR effects are mainly due to cutoff rigidity variations that are most intense during great geomagnetic storms.

CR cutoff rigidities can be obtained mainly on the basis of particle trajectory calculations in the magnetic field of any magnetosphere model McCracken et al., M1962, M1965; Dorman et al., M1971, M1972; Shea and Smart, M1975; Shea et al., M1976; see details in Chapter 3). Empirical magnetosphere models are widely used for this purpose. The accuracy in determining geomagnetic cutoff rigidities substantially depends on the magnetospheric model used in the calculations. Empirical magnetosphere models take into account theoretical representations of dynamical processes in the magnetosphere from one side and direct magnetic field measurements in space from another side. Strong geomagnetic storms are relatively rare events, therefore the data of very disturbed periods represent a small part of the data used in the derivation of empirical geomagnetic field models. This circumstance explains why the magnetospheric magnetic field model for strong magnetospheric disturbances did not exist until recent times.

For checking the magnetosphere models for great magnetic storms presented in Tyasto et al. (2008) we used the same case as considered in Section 7.6: period of November 18–24, 2003. To calculate geomagnetic cutoff rigidities during disturbed period of November 18–24, 2003 we used the Tsyganenko magnetosphere model Ts03 which was derived on the basis of measurements during 37 geomagnetic storms with $D_{\rm st} \leq -65$ nT (Tsyganenko, 2002a, b; Tsyganenko et al., 2003). This model describes a strong disturbed configuration of the magnetospheric magnetic field and its evolution during the storm.

Another way of determining geomagnetic cutoff rigidities is to use the spectrographic global survey (SGS) method which is based on the assumption that the anisotropy in the CR distribution along the directions of arrival is attributed to the dependence of their intensity on pitch angle in the interplanetary magnetic field and to a density gradient (Dvornikov and Sdobnov, 2002). Variation amplitudes of an integral flux of secondary particles $\Delta N_c/N_{co}$ (with respect to a certain background level N_{co}) observed at a geographical site with cutoff rigidity R_{co} at level h_o in the earth's atmosphere may be represented as follows:

$$\Delta N_{\rm c}/N_{co} = -\Delta R_{\rm c} W_{\rm c} \left(R_{\rm co}, R_{\rm co}, h_o\right) \times \left[1 + \frac{\Delta D \left(R_{\rm co}\right)}{D_o \left(R_{\rm co}\right)}\right] + \int_{0}^{2\pi} \int_{0}^{\pi/2} \sin\beta d\beta \int_{R_{\rm co}}^{\infty} \frac{\Delta D}{D_o} \left(R, \Psi(R, \alpha, \beta), \Lambda(R, \alpha, \beta)\right) W_{\rm c} \left(R_{\rm co}, R, \beta, h_o\right) dR,$$
(7.57)

where α and β are the azimuth and zenith angles of arrival of primary CR particles at the atmospheric boundary, $W_c(R_{co}, R, \beta, h_o)$ is the coupling function between

primary and secondary CR variations; $\Psi(R, \alpha, \beta)$ and $\Lambda(R, \alpha, \beta)$ are asymptotic angles of arrival of CR particles. The dependence $\Delta R_c(R_{co})$ was approximated as

$$\Delta R_{\rm c}(R_{\rm co}) = \left(b_1 R_{\rm co} + b_2 R_{\rm co}^2\right) \frac{\exp\left(-\sqrt{R_{\rm co}}\right)}{1 + \frac{a_1}{R_{\rm co}} + \frac{a_2}{R_{\rm co}^2} + \frac{a_3}{R_{\rm co}^3}}.$$
(7.58)

The system of Eq. 7.57 for each CR station from the NM worldwide network was used to calculate the change of geomagnetic cutoff rigidities on the basis of NM data corrected for atmospheric effects.

7.7.2 Comparison ΔR_{sgs} Derived from CR Data and ΔR_{ef} Obtained by Trajectory Tracing Within in the Frame of the Ts03 Tsyganenko Model

Using the SGS method, we obtain CR cutoff rigidity variations (with respect to the quiet level of October 12, 2003) ΔR_{sgs} for every hour of the geomagnetic storm of November 18–24, 2003.

On the other hand, the effective cutoff rigidities ΔR_{ef} were calculated in the magnetic field of the Ts03 model by the trajectory tracing method for Tokyo, Alma-Ata, Rome, Irkutsk, Moscow, and Hobart NM stations. Quiet cutoff rigidities of the chosen stations occupy the main part of the cutoffs influenced on CRs by the geomagnetic field. Effective cutoff rigidity changes ΔR_{ef} were also determined with respect to the quiet level of October 12, 2003. The daily averaged effective cutoffs at October 12, 2003 are 11.02 GV (Tokyo), 6.19 GV (Alma-Ata), 6.08 GV (Rome), 3.25 GV (Irkutsk), 2.10 GV (Moscow), and 1.75 GV (Hobart). It is necessary to notice that these cutoff rigidities are lower by 0.2–0.4 GV than the rigidity cutoffs in the main geomagnetic field.

Figure 7.37 displays the time variations in the calculated cutoff rigidities obtained by the two above-named different methods ΔR_{ef} (open circles) and ΔR_{sgs} (crosses) during November 18–24, 2003. The curves in six upper panels in Fig. 7.37 correspond to the Tokyo, Alma-Ata, Rome, Irkutsk, Moscow, and Hobart NM stations. The lower part of Fig. 7.37 shows the D_{st} -variation (filled circles), Kp-index (open circles), and the dynamic pressure P_{sw} of the solar wind. It is seen in Fig. 7.37 that curves ΔR_{ef} and ΔR_{sgs} are in general consistent with each other and with the D_{st} -variation. Some differences between ΔR_{ef} and ΔR_{sgs} are noticeable at the D_{st} minimum for Moscow and Hobart. Maximum decreases of the geomagnetic cutoffs are observed for November 20, 2003 during the main phase of the geomagnetic storm but the hours of maximum geomagnetic cutoff decreases do not always coincide with D_{st} -minimum ones.



Fig. 7.37 CR cutoff rigidity variations during November 18–24, 2003 (From Tyasto et al., 2008)

Station	Δl	R _{ef}	ΔR	ΔR_{sgs}		
	(GV)	(%)	(GV)	(%)		
Tokyo	-0.8	-7.2	-1.06	-9.6		
Alma-Ata	-1.18	-19.1	-1.30	-21.0		
Rome	-1.33	-21.9	-1.32	-21.7		
Irkutsk	-1.67	-51.4	-1.63	-50.2		
Moscow	-1.81	-86.2	-1.62	-77.1		
Hobart	-1.51	-86.3	-0.96	-54.9		

Table 7.6 Decreases of the CR cutoff rigidities during the D_{st}-minimum (From Tyasto et al., 2008)

7.7.3 Comparison of Absolute and Relative Maximum Decreases of CR Cutoff Rigidities

A comparison of absolute and relative maximum decreases of CR cutoff rigidities at each of the six chosen stations, and a comparison between results derived from CR data and obtained by trajectory calculations are shown in Table 7.6.

As seen in Table 7.6, the percentage cutoff rigidity decreases at low-latitude stations are similar. At middle-latitude stations Irkutsk, Moscow, and Hobart geomagnetic cutoffs decreased by 50–85%. This means that the cutoff rigidity of Moscow at the $D_{\rm st}$ -minimum time, for example, became less than the cutoff of the auroral zone station Apatity during quiet periods.

7.7.4 The Behavior of the Difference $\delta R_{c} = \Delta R_{sgs} - \Delta R_{ef}$

Figure 7.38 shows the difference $\delta R_c = \Delta R_{sgs} - \Delta R_{ef}$ for all chosen stations (symbols are the same). Positive values δR_c predominate mainly at times before D_{st} -minimum for all stations except Hobart. Irregularities of the curves δR_c are more noticeable during the main and recovery phase of the magnetic storm. Values δR_c for Irkutsk and Moscow are positive at given times and in the D_{st} -minimum and δR_c for Hobart is rather big during the D_{st} -minimum. Sometimes geomagnetic cutoffs R_{ef} are systematically slightly lower than R_{sgs} . Differences between ΔR_{sgs} and ΔR_{ef} are in limits of $\pm 0.7 \,\text{GV}$ with the main part of differences in the limits of $\pm 0.4 \,\text{GV}$.

7.7.5 On the Correlations of ΔR_{sgs} and ΔR_{ef} with Parameters D_{st} , B_Z , B_Y , N_{SW} , and V_{SW}

It is very interesting to see how geomagnetic and interplanetary parameters are reflected in cutoff rigidity variations of ΔR_{sgs} and ΔR_{ef} . The D_{st} , B_Z , B_Y , N_{SW} , V_{SW} are



Fig. 7.38 The same as in Fig. 7.37, but for $\delta R_c = \Delta R_{sgs} - \Delta R_{ef}$ (From Tyasto et al., 2008)

Station	$D_{\rm st}$	B_Z	B_Y	Density N _{sw}	Velocity V _{sw}
Tokyo	0.98	0.66	0.18	0.68	0.06
Alma-Ata	0.98	0.68	0.18	0.68	0.05
Rome	0.98	0.71	0.18	0.67	0.05
Irkutsk	0.98	0.72	0.16	0.69	0.04
Moskow	0.98	0.69	0.14	0.69	0.04
Hobart	0.96	0.71	0.08	0.68	0.05

Table 7.7 Correlation coefficients of the ΔR_{ef} with geomagnetic and interplanetary parameters (From Tyasto et al., 2008)

Table 7.8 Correlation coefficients of the ΔR_{sgs} with geomagnetic and interplanetary parameters (From Tyasto et al., 2008)

Station	$D_{\rm st}$	B_Z	B_Y	Density $N_{\rm sw}$	Velocity V _{sw}
Tokyo	0.66	0.26	0.43	0.37	0.08
Alma-Ata	0.81	0.35	0.48	0.46	0.15
Rome	0.82	0.37	0.47	0.47	0.16
Irkutsk	0.87	0.49	0.38	0.56	0.14
Moskow	0.86	0.55	0.29	0.56	0.12
Hobart	0.78	0.48	0.16	0.55	0.17

geomagnetic and interplanetary input parameters of the Ts03 model. Coefficients of correlation between these parameters with ΔR_{ef} and ΔR_{sgs} are shown in Tables 7.7 and 7.8, respectively.

Table 7.7 shows that correlation coefficients of $\Delta R_{\rm ef}$ with the $D_{\rm st}$ -variation, B_Z component of the IMF and the solar wind density $N_{\rm SW}$ are rather high with the
highest for correlations with $D_{\rm st}$ for every station. The $B_{\rm Y}$ -component of the IMF
and the solar-wind velocity $V_{\rm sw}$ are weakly reflected or nearly not reflected in $\Delta R_{\rm ef}$ if correlation coefficient values are taken into account.

Correlation coefficients between ΔR_{sgs} and D_{st} , B_Z and N_{SW} are less than the coefficients in the previous case but are sizable enough (see Table 7.8). As before, correlation of ΔR_{sgs} with D_{st} is highest and with V_{SW} is lowest, respectively. Component B_Y of the IMF has a closer relation with ΔR_{sgs} than with ΔR_{ef} . This circumstance can indicate that a dawn–dusk asymmetry of the Ts03 model magnetosphere is not approximated exactly enough.

7.7.6 On the Relations Between ΔR_{sgs} and ΔR_{ef} for Different CR Stations

It is also interesting to see how ΔR_{ef} and ΔR_{sgs} correspond to each other. Figure 7.39 displays scatter plots of the ΔR_{ef} against the ΔR_{sgs} for different CR stations and the approximating regression lines.


Fig. 7.39 Scatter plots of ΔR_{ef} against ΔR_{sgs} with regression lines for different CR stations (From Tyasto et al., 2008)

In Fig. 7.39 correlation coefficients are rather high and equal to 0.63, 0.77, 0.78, 0.84, 0.84, and 0.76 for Tokyo, Alma-Ata, Rome, Irkutsk, Moscow, and Hobart, correspondingly. It is clearly seen that the slopes of the best linear fit to the scatter plots depend on the station's latitude being minimum for the low-latitude station Tokyo and maximum for the middle-latitude station Hobart.

7.7.7 Main Results and Conclusion

Analysis shows that CR cutoff rigidity variations ΔR_{ef} and ΔR_{sgs} determined by two quite different methods are similar in general during the considered geomagnetic storm. CR cutoff rigidities obtained by both methods, decrease substantially during the D_{st} -minimum so that the geomagnetic cutoff at Moscow becomes less than the cutoff rigidity at the auroral zone station Apatity during quiet periods. The main parts of cutoff rigidity variations are connected with the D_{st} -variation. The influence of the solar-wind density N_{sw} and B_Z -component of IMF in ΔR_{sgs} is less noticeable than in ΔR_{ef} but the influence of B_Y -component of IMF on the contrary is seen in ΔR_{sgs} more clearly. Maybe it points out that dawn–dusk asymmetry in the Ts03 model was not approximated enough. Coefficients of correlation between ΔR_{ef} and ΔR_{sgs} lay in the limits 0.63–0.84 for stations with geomagnetic cutoffs from 1.75 GV to 11.02 GV at quiet periods to have maximum at middle-latitude stations Moscow and Hobart. The dependence of ΔR_{ef} on ΔR_{sgs} demonstrates that the slopes of the best linear fit to the scatter plots depend on the station's latitude to be minimum for the low-latitude station Tokyo and maximum for the middle-latitude station Hobart.

7.8 Checking of Magnetosphere Models by Solar CRs: GLE on January 20, 2005

7.8.1 The Matter of Problem

In Sections 7.4–7.7 we considered different possibilities to check the magnetosphere models on the basis of using galactic CRs. In principle, for checking the magnetosphere models, solar CRs of great events occurring during big magnetic storms may also be used. One very interesting example was considered by Struminsky (1992, 2001) and Struminsky and Manohar (2001) of GLE on October 20, 1989 during a strong magnetic storm (see above in Chapter 6, Section 6.25). Another very interesting example was considered by Flückiger et al. (2006): the GLE on January 20, 2005 also occurred during a strong magnetic storm.

7.8.2 CR Data of NM on Mt. Jungfraujoch in Comparison with Other NM Data

In Fig. 7.40, counting rate of IGY NM on high-altitude station Jungfraujoch are shown; this figure also shows the start of two geomagnetic SSC on January 17 and 21, 2005, and the start of X7.1 solar flare. One-minute data of NM at Jungfraujoch are shown in Fig. 7.41.



Fig. 7.40 The counting rate of IGY NM on high-altitude station Jungfraujoch in January, 2005 (From Flückiger et al., 2006)



Fig. 7.41 One-minute data of IGY NM on Jungfraujoch at January 20, 2005 (From Flückiger et al., 2006)

In Fig. A7.13 variations of the NM counting rate during hours 6–8 of January 20, 2005 at Jungfraujoch are shown in detail in comparison with high-latitude NM on stations Terre Adelie, South Pole, Inuvik, and Barentsburg, where the amplitude of increase was from 10 to 300 times larger. The problem is that this GLE occurred during a great magnetic storm, so it is necessary to correct all CR observation data of this GLE on geomagnetic variations.



Fig. 7.42 Variations of geomagnetic indexes in January 2005 during magnetic storms and GLE (From Flückiger et al., 2006)

7.8.3 Determining CR Cutoff Rigidity Variations During GLE within the Frame of Tsyganenko Models of Disturbed Magnetosphere; Correction of CR Data on Geomagnetic Variations

Flückiger et al. (2006) used data of more than 20 CR stations; for all stations corrections were introduced on geomagnetic variations calculated on the basis of measurements of D_{st} and K_p indexes of geomagnetic activity (see Fig. 7.42) within the frame of Tsyganenko models (see Section 7.1) by using the calculation procedure of Desorgher (2004). In Fig. A7.14 results are shown of these calculations for planetary distribution of expected cutoff rigidities for the moment of the GLE starting (06.56 UT at January 20, 2005). The difference between CR cutoff rigidity for each used NM determined from Fig. A7.14 and CR cutoff rigidity for the quiet period give the CR cutoff rigidity variation ΔR_c .

On the basis of the obtained results, Flückiger et al. (2006) estimated the expected geomagnetic CR variations on each used CR station:

$$\left(\Delta N_i(t)/N_{io}\right)_{\text{geomag}} = -\Delta R_c W_i(R_{co}, R_{co}, h_o), \qquad (7.59)$$

where $W_i(R_{co}, R_{co}, h_o)$ is the response (coupling) function for corresponding station. All CR data of more than 20 NM were corrected on these geomagnetic variations. Flückiger et al. (2006) showed that for middle- and low-latitude stations where the amplitude of CR increase during GLE was not so big (as at NM on Jungfraujoch), these corrections are very important.

7.8.4 Determining Solar CR Angle Distribution and Energy Spectrum Time Variations, and Checking Self-Consistent CR Data with Tsyganenko's Magnetosphere Model

The found extraterrestrial CR variations were analyzed and pitch-angle distribution at different moments of time (see Fig. 7.43) and the variation of the differential energy spectrum of solar CRs with time (see Fig. 7.44) were determined. Flückiger et al. (2006), on the basis of obtained results, shown in Figs. 7.43 and 7.44, came to the conclusion that the inter-consistence of all CR data from more than 20 stations of the worldwide NM network after correction on geomagnetic variations within the frame of Tsyganenko's disturbed magnetosphere model shows that this model mostly reflects the disturbed magnetic field and currents in the earth's magnetosphere.



Fig. 7.43 The pitch-angle distributions of solar CR in the initial, main, and decay phases of GLE January 20, 2005 obtained by using CR observation data from more than 20 stations after correction on geomagnetic variations according Fig. A7.14 (From Flückiger et al., 2006)



Fig. 7.44 The variation in time parameters a(t) and $\gamma(t)$ of differential solar CR spectrum $D_{sol} = a(t)R^{-\gamma(t)}$ during GLE January 20, 2005; obtained by using CR observation data from more than 20 NM stations after correction on geomagnetic variations within the frame of Tsyganenko's disturbed magnetosphere model according to Fig. A7.14 (From Flückiger et al., 2006)

Chapter 8 Galactic Cosmic Rays in Atmospheres and Magnetospheres of Other Planets

8.1 The Matter of Problem

In connection with the extensive program of detailed study of the CR and accelerated particles in the vicinities of the solar planets carried out in the last 40 years, it is of interest to estimate the expected properties of the CR secondary components, the integral generation multiplicities, the coupling functions, and the meteorological and magnetic effects for the planets and satellites. However, as I mentioned in Preface, to our pity we did not found in scientific literature any papers devoted to the problem of CR behavior in atmospheres and magnetospheres of other planets and satellites, except two papers of the author and his colleagues in which we consider only planets Venus, Mars, and Jupiter.

First of all, we will briefly discuss the properties of atmospheres of these and some other planets and satellites (Section 8.2). The results of the calculations and estimation of the parameters of the CR secondary components will be presented in Section 8.3 for the planet Mars (the Martian atmosphere has been well studied and, besides, the CR measurements on the Martian surface are most promising; so the most detailed calculations will be presented for this planet) and in Section 8.4 for planets Venus and Jupiter (the atmospheres of these planets are characterized by very high pressures on the planetary surfaces, which makes it possible to use an approximate method when estimating the coupling functions).

8.2 The Properties of the Planetary Atmospheres

The meteorological conditions in the planetary atmospheres are discussed in Kondratyev (M1977), and Chamberlain and Hunten (M1987). Ingersoll et al. (1979) have reviewed the results of the studies of the atmospheres of Venus, Mars, Jupiter, the outer planets, and their satellites obtained by the end of 1978 from space probes and from ground-based instruments. The review of the dynamics of the atmospheres

of Jupiter and its satellites Io and Ganymede, Saturn and its satellite Titan, Uranus, Neptune, and Pluto is presented in Golitsyn (1979). The dimensionless similarity parameters characterizing the thermal energy of the planetary atmospheres, the seasonal effects, and the role of the diurnal rotations are also presented. The similarity parameters include the Mach number and the ratio of the altitude scale to the equatorial radius. The atmospheres of Titan, Pluto, Neptune, Uranus, Saturn, and Jupiter are from radiation equilibrium and their thermal conditions are mainly determined by the dynamics. The dynamics of the atmospheres of Io and Ganymede is determined by their thermal conditions. The low densities result in similar properties of the dynamics of the atmospheres of these planets and satellites and those of the terrestrial planets, but in the presence of the specific boundary layer. The thermal conditions are closely associated with the surface conditions; the wind velocity is of the order of the sonic velocity. Some similar and different features of the dynamics of Titan (and probably Pluto) and the circulation of Venus are noted. The hydrodynamic analogies between the oceanic dynamics and the dynamics of the Jovian atmosphere are presented. The solution hypothesis of the circulation disturbances on Jupiter's disc is discussed. The existence of two rotational periods of Neptune may be interpreted as evidence for an equatorial jet with relative velocity $\sim 140 m/s$ on this planet. Presented below will be some data on the Venusian atmosphere. According to Kondratyev (M1977), the atmosphere is sufficiently extended (the altitude of the 1-bar isobar is about 60 km), very dense, and consists largely of carbon dioxide; the pressure near the planetary surface reaches 90 bar. The gas temperature near the surface is 750°K. Because of a significant greenhouse effect, the temperature of the Venusian atmosphere is practically constant; only slight diurnal variations are observed. The data characterizing the composition of the lower Venusian atmosphere are presented in Oyama et al. (1979). The data have been obtained on the basis of the measurements with a gas chromatograph. Three samples of air, Nos. 1, 2, and 3, were collected at altitudes of 54 km at 0.698 \pm 0.140 bar pressure, 44 km at 2.91 ± 0.17 bar, and 24 km at 17.7 ± 0.2 bar, respectively. The data obtained are presented in Table 8.1.

Gas	No. of sample		
	1	2	3
	Concentration (%	b) \pm the reliability interval (3 σ)
CO ₂	95.4 + 4.6 / -20.1	95.9 + 4.1 / -5.85	96.4 ± 1.03
N_2	4.6 ± 0.088	3.54 ± 0.026	3.41 ± 0.021
H ₂ O	0.06	0.519 ± 0.068	0.135 ± 0.015
	Concentration (parts per	million) \pm the reliability inter	val (3σ)
02	59.2 ± 25.2	65.6 ± 7.32	69.3 ± 1.27
Ar	30.3 + 46.9 / -20.3	28.3 + 13.7	18.6 + 2.37
Ne	8	10.6 + 31.6 / - 9.6	4.31 + 5.54 / -3.91
SO ₂	600	176 + 200 / -150	186 + 349 / -156

Table 8.1 Composition of the Venusian atmosphere (From Oyama et al., 1979)

The upper limits of the concentration of other components (H₂, CO, CH₄, Kr, N_2O , C_2H_4 , C_2H_6 , C_3H_8) may be estimated taking account of the delectability limit. The presented results are in good agreement with the data obtained from Venera-9, 10 space probes, excluding the data on argon which proved to be overestimated (its concentration was found to be ~ 200 parts per 1 million) in the mass-spectrometer measurements on Venera-9 and 10. The gas-chromatograph measurements confirm that water vapor makes an important contribution to the overlap of the CO_2 transparence windows and to the maintenance of the greenhouse effect. The gaschromatograph data agree with the sulphuric-acid composition of the Venusian upper clouds. The possible upper limit of the CO concentration at the 24-km altitude does not exceed 0.6 parts per 1 million. It should be concluded, therefore, that CO is produced in photochemical processes only. The significant O_2 concentration in the lower atmosphere is probably indicative of a higher degree of oxidation in the present-day atmosphere as compared with that in the geological past, a fact that may be explained by the effect of the water vapor dissociation with subsequent dissipation of molecular hydrogen.

The probing of the Venusian atmosphere with a mass-spectrometer from Pioneer-Venus spacecraft (Hoffman et al., 1979) has yielded the data on the composition of the atmosphere in the interval of masses from hydrogen to lead. The examination of 55 mass spectra (the scanning time of each of the spectra in the 1-208 a.m.u. range is 64 s, which permits a 1 km altitude resolution) has shown surprisingly high concentrations of ³⁶Ar, ³⁸Ar, and ²⁰Ne. The volume ratio of the ³⁶Ar mixture is about 10^{-4} , whereas its value in the earth's atmosphere is 3.2×10^{-5} . Since the Venusian atmosphere mass is about 90 times the earth's atmosphere mass, the absolute ³⁶Ar content in the Venusian atmosphere should be 200–300 times its value in the earth's atmosphere. The 36 Ar/ 38 Ar concentration ratio has proved to be about the same as that for the earth, meteorites, and the moon. The value of the ${}^{36}\text{Ar}/{}^{12}\text{C}$ ratio for Venus suggests that the major portion of ³⁶Ar and ¹²C is contained in the atmosphere. On the earth, the same is observed for ${}^{36}Ar$, whereas ${}^{12}C$ is concentrated in the carbonate materials. The ⁴⁰Ar content on Venus is about the same as on the earth. The pressure of the neutral gas (mainly CO_2) in the very rarefied atmosphere of Mars Kondratyev, M1977) is only 7 mbar near the planetary surface. The altitude of the 0.7 mbar isobar is about 20 km.

In the much extended and highly dense atmosphere of Jupiter, the pressure of the neutral gas (mainly hydrogen) reaches 20 bars near the planetary surface. The altitude of the 1 bar isobar is about 200 km (Kondratyev and Moskalenko, 1976; Krupenko, M1978). The Jovian atmosphere is probably characterized by a very low variability of temperature in the layers under the clouds since the temperature conditions in the Jovian atmosphere is largely determined by the existence of the internal sources of heat.

8.3 The CR Secondary Components, the Integral Generation Multiplicities, and the Coupling Functions in the Martian Atmosphere; Expected Latitude Magnetic Effect

The Martian atmosphere has been most studied among the terrestrial planets. This fact justifies specific numerical calculations for Mars. Such calculations can be significantly simplified because but a single interaction of the particles incident on the Martian surface may be used (Dorman et al. 1979a). In fact, in the Martian atmosphere, the thickness of matter traversed by the primary CR particles is one order as small as the interaction path, so that the probability of two and more interactions of even a horizontally incident nucleon is only 5–10%. Moreover, if the energy loss is neglected, our problem will be significantly simplified.

On the above assumptions, the kinetic equations describing the development of one-dimensional hadron cascade produced by a primary single nucleon with energy E_{ρ} in the Martian atmosphere arriving at zenith angle θ are of the form

$$\frac{\partial N_n(E,h,\theta)}{\partial h} = -\frac{N_n(E,h,\theta)}{\lambda_n(E)\cos\theta} + \int_E^{E_0} \frac{N_n(E',h,\theta)}{\lambda_n(E')\cos\theta} f_{nn}(E',E) dE'$$
(8.1)

for nucleons and

$$\frac{\partial N_{\pi}(E,h,\theta)}{\partial h} = -\frac{b_{\pi}N_{\pi}(E,h,\theta)}{E\rho(h)\cos\theta} + \int_{E}^{E_{o}} \frac{N_{n}(E',h,\theta)}{\lambda_{n}(E')\cos\theta} f_{n\pi}(E',E) dE'$$
(8.2)

for pions. The solutions of Eqs. 8.1 and 8.2 for a single primary nucleon with energy E_o are

$$N_n(E,h,\theta) = exp\left(-\frac{h}{\lambda_n(E_o)}\right) \left[\delta(E-E_o) + \frac{hf_{nn}(E_o,E)}{\lambda_n(E_o)\cos\theta}\right],\tag{8.3}$$

$$N_{\pi}(E,h,\theta) = \frac{hf_{n\pi}(E_o,E)}{\lambda_n(E)\cos\theta} \left(1 + \frac{b_{\pi}H_o}{E\cos\theta}\right),\tag{8.4}$$

where $f_{n\eta}$ is the generation spectrum of the particles of type η with energy *E* in the nucleon–nucleon interaction (in our case, we consider generation of nucleon, $\eta = n$, or generation of pion, $\eta = \pi$); $b_{\pi} = m_{\pi}/\tau_{\pi}c$ is the decay constant for pions $(m_{\pi} \text{ and } \tau_{\pi} \text{ are the mass and decay time of charged rest pions,$ *c* $is the velocity of light); <math>H_o = 3.5 \times 10^5$ cm is the height of the homogeneous atmosphere. The integral multiplicity of nucleon generation $m_{1n} (E_o, h_o, \theta)$ will be determined by integrating the solution, described by Eq. 8.3, over all the secondary particle energies. Then,

$$m_{1n}(E_o, h_o, \theta) = \exp\left(-\frac{h}{\lambda_n(E_o)\cos\theta}\right) \left[1 + \frac{h_o m_{nn}(E_o)}{\lambda_n(E_o)}\right],\tag{8.5}$$

where $m_{nn}(E_o)$ is the multiplicity of nucleons in the nucleon–nucleon elementary act of interaction. It is also necessary that the contribution $m_{2n}(E_o, h_o, \theta)$ from the δ -nucleus produced in the nucleon–nucleus interactions should be included. It has been shown in Barashenkov and Toneev (M1972) that the number of δ -nucleons in an elementary interaction event of a given nuclei is

$$m_{n\delta}(E_o) = \begin{cases} 0.81 E_o^{0.46} \text{ if } E_o \le 5 \text{ GeV}, \\ 1.7 \text{ if } E_o \le 5 \text{ GeV}. \end{cases}$$
(8.6)

Considering the δ -nucleon absorption in the atmosphere with absorption path *L*, the integral multiplicity $m_{2n}(E_o, h_o, \theta)$ of the nucleon interaction at the level h_o is

$$m_{2n}(E_o, h_o, \theta) = \frac{h_o m_{n\delta}(E_o)}{\lambda_n(E_o)\cos\theta} \exp\left(-\frac{h_o}{L\cos\theta}\right).$$
(8.7)

The total integral generation multiplicity calculated using Eqs. 8.5 and 8.7 will be

$$m_{n}(E_{o},h_{o},\theta) = m_{1n}(E_{o},h_{o},\theta) + m_{2n}(E_{o},h_{o},\theta) = \exp\left(-\frac{h}{\lambda_{n}(E_{o})\cos\theta}\right) \times \left[1 + \frac{h_{o}m_{nn}(E_{o})}{\lambda_{n}(E_{o})}\right] + \frac{h_{o}m_{n\delta}(E_{o})}{\lambda_{n}(E_{o})\cos\theta}\exp\left(-\frac{h_{o}}{L\cos\theta}\right).$$
(8.8)

The total integral generation multiplicity calculated using Eq. 8.8 on the planetary surface is shown in Fig. 8.1 (with results also for the muon component); the coupling function of the nucleon component is presented in Fig. 8.2.



Fig. 8.1 The integral multiplicity for nucleons and muons in the Martian atmosphere (From Dorman et al., 1979a)





Consider now the muon component. On finding the flux of pions with energy E_{π} at depth *h*, it will be possible to determine the number of the muons produced in the decays of these pions at depth *h* in the layer *dh*:

$$f_{\mu}(E_{\pi},h,\theta)dh = \frac{b_{\mu}N_{\pi}(E_{\pi},h,\theta)dh}{E_{\pi}\rho(h)\cos\theta},$$
(8.9)

where $b_{\mu} = m_{\mu}/\tau_{\mu}c$ is the decay constant for muons (m_{μ} and τ_{μ} are the mass and decay time of rest muons), and $\rho(h)$ is the density of the Martian atmosphere.

The decay of a pion with energy E_{π} gives a muon with average energy $E_{\mu} = \alpha E_{\pi}$, where $\alpha = m_{\mu}/m_{\pi}$. The probability $\varphi_{\mu} (E_{\pi}, h, h_o, \theta)$ for muons with energy $E_{\mu} = \alpha E_{\pi}$, produced by the pions with energy E_{π} , to traverse at zenith angle θ the path from their generation level *h* to a certain observation level h_o is

$$\varphi_{\mu}\left(E_{\pi},h,h_{o},\theta\right) = exp\left(-b_{\mu}\int_{h}^{h_{o}}\frac{\mathrm{d}h'}{\alpha E_{\pi}\rho\left(h'\right)\cos\theta}\right) \approx \left(\frac{h}{h_{o}}\right)^{\frac{b_{\mu}H_{o}}{\alpha E_{\pi}\cos\theta}}.$$
(8.10)

Then the integral generation multiplicity of the muons with energies exceeding ΔE_{μ} incoming to the observation level h_o will be

$$m_{\mu}\left(E_{o},h_{o},\theta,\Delta E_{\mu}\right) = \int_{\Delta E_{\mu}} / \alpha^{E_{o}} \mathrm{d}E_{\pi} \int_{\mathbf{0}}^{h_{o}} \mathrm{d}h \frac{b_{\pi}H_{o}N_{\pi}\left(E_{\pi},h,\theta\right)}{E_{\pi}\rho\left(h\right)\cos\theta} \left(\frac{h}{h_{o}}\right)^{\frac{b_{\mu}H_{o}}{\alpha E_{\pi}\cos\theta}}.$$
 (8.11)

The integration over h gives the eventual expression of the integral generation multiplicity of muons

$$m_{\mu}\left(E_{o},h_{o},\theta,\Delta E_{\mu}\right) = \frac{b_{\pi}H_{o}h_{o}}{\lambda_{n}\left(E_{o}\right)\cos^{2}\theta} \int_{\Delta E_{\mu}/\alpha}^{E_{o}} \frac{f_{n\pi}\left(E_{o},E_{\pi}\right)dE_{\pi}}{\left(1+\frac{b_{\pi}H_{o}}{E_{\pi}\cos\theta}\right)\left(1+\frac{b_{\mu}H_{o}}{\alpha E_{\pi}\cos\theta}\right)}$$
(8.12)

The integral generation multiplicity of muons is shown in Fig. 8.1 and the relevant coupling function on the Martian surface near solar minimum in Fig. 8.2.

The magnetic cutoff rigidity along a vertical on the magnetic equator is below 0.02 GV. This value has been inferred from the data on the Martian magnetic moment (Dolginov et al., 1975). It follows from the above that the expected latitude magnetic effect of CR on the Martian surface is negligible and may be neglected. It will be noted that the expected intensity of the muon component on the Martian surface is approximately two times as low as the muon component intensity on the earth's surface and that the nucleon component intensity is more than three orders as high as the nucleon component intensity on the earth's surface.

8.4 The CR Secondary Components, the Integral Generation Multiplicities, and the Coupling Functions in the Atmospheres of Jupiter and Venus; Expected Latitude Magnetic Effect

The parameters characterizing the states of the Venusian and Jovian atmospheres (the neutral-gas pressure the altitude distribution of temperature, the composition of the atmospheres) are determined mainly by the radio astronomy method and, partly, by direct measurements on board space probes. Since the present-day accuracy of such data is low, detailed calculations to determine the integral multiplicity of the different secondary components generation in the interactions of the primary CR with the atmospheric matter are inexpedient. It is quite sufficient, therefore, to use the semi-empirical methods for determining the coupling functions (Dorman et al., 1979b). Because of a very high density of the Venusian atmosphere, the nucleon component is almost completely absorbed so that the very high-energy muons (whose minimum energy ΔE_{μ} in vertical direction is estimated to be 290 GeV) may only reach the planetary surface. The lifetime of such particles is more than one order in excess of the time of the traversal of even the relatively extended atmosphere of Venus. This circumstance permits the neglect of the muon decays in the atmosphere and the determination of the coupling functions by semi-empirical methods.

The same reasoning is valid in practice for the applicability of the semi-empirical methods to the much extended atmosphere of Jupiter. In this case, however, the minimum energy ΔE_{μ} of the muons which can reach the planetary surface is 115 GeV. The lifetime of such particles is but a little in excess of the time of the traversal of

the planetary atmosphere. Obviously, the muon decays in the atmosphere become significant. It was assumed in Dorman et al. (1979b), when using the semi-empirical methods, that the coupling functions in the Venusian and Jovian atmospheres at depths with residual pressure 1 bar were the same as those at sea level in the earth's atmosphere. This assumption is sufficiently justified in the case of the Venusian atmosphere, since the atmospheres of Venus and earth consist of gas with similar mean mass numbers and similar mean molecular weights. The acceleration due to gravity on the two planets is also slightly different.

The accuracy of the assumption in the case of the Jovian hydrogen atmosphere is lower. It is necessary, before determining the coupling functions, to find the pathenergy dependence in a particular atmosphere and the maximum portion of the primary particle energy χ transferred to muon. We shall assume that $\chi = 0.5$. Such value of χ gives satisfactory results when the semi-empirical method is used to estimate the underground coupling functions on the earth (see Chapter 3 in Dorman, M2004). Thus, $E_{\min} = \Delta E_{\mu} / \chi$.

The following remarks should be made concerning the path energy relationship, i.e., the energy ΔE_{μ} lost by muons on traversing the entire atmospheric depth. Since the muon energy is sufficiently high, not only the ionization loss but also the loss for pair production, for bremsstrahlung and for the nuclear interactions of muons should be included.

The coupling function of the muon component $W_{\mu} (\Delta E_{\mu 2}, E_o)$ on the planetary surface will be determined using the known coupling function $W_{\mu} (\Delta E_{\mu 1}, E_o)$ which relates, in our case, to the depth with residual pressure 1 bar so that the sought coupling function is according to the first semi-empirical method developed in Dorman (M1957); see also Chapter 3 in Dorman (M2004):

$$W_{\mu}\left(\Delta E_{\mu 2}, E_{o}\right) = \begin{cases} bW_{\mu}\left(\Delta E_{\mu 2}, E_{o}\right) \text{ if } E_{o} \ge E_{\min},\\ 0 \qquad \text{ if } E_{o} < E_{\min} \end{cases}$$
(8.13)

and the factor *b*, which depends on $E_{\min} = \Delta E_{\mu 2} / \chi$, is determined by the normalization condition

$$b\int_{E_o}^{\infty} W_{\mu} \left(\Delta E_{\mu 2}, E_o\right) dE_o = 1.$$
(8.14)

The coupling functions found by the above method are very approximate mainly because of the fact that the coupling functions $W_{\mu} (\Delta E_{\mu 1}, E_o)$ are used in the extrapolation domain where their values are insufficiently reliable, with a pronounced boundary at the low-energy side and an approximate estimate of the boundary energy proper which is determined by the choice of χ .

In the second semi-empirical method developed in Dorman and Feinberg (1959) (see also Chapter 3 in Dorman, M2004), the sought coupling function is determined as

$$W_{\mu}\left(\Delta E_{\mu 2}, E_{o}\right) = \frac{\Delta E_{\mu 1}}{\Delta E_{\mu 2}} W_{\mu}\left(\Delta E_{\mu 1}, \frac{\Delta E_{\mu 2}}{\Delta E_{\mu 1}} E_{o}\right), \qquad (8.15)$$



i.e., it is assumed that the shape of the dependence of $W_{\mu} (\Delta E_{\mu 2}, E_o)$ for any $\Delta E_{\mu 2}$ on E_o , plotted on a double-logarithmic scale, is the same for all the depths. This assumption is not quite correct since the calculations for various threshold energies show that the energy dependence of the integral multiplicity is somewhat variable. Besides that, some uncertainty remains in determining $\Delta E_{\mu 1}$ and $\Delta E_{\mu 2}$. In this case, however, more reliable results, as compared with the first semi-empirical method, may be expected. The coupling functions found for the Venusian and Jovian atmospheres are shown in Figs. 8.3 and 8.4.

It is known that the integral multiplicity in the high-energy range may be approximated by the power-law function $\propto E_o^\beta$ (see in detail Chapter 3 in Dorman, M2004). In this case, the coupling functions in the high-energy range may be approximated by the function $\propto E_o^{-(\gamma-\beta)}$, where γ is the power-law exponent of the primary CR differential spectrum. In view of a certain uncertainty in the experimental value of γ and in the value of β , the coupling functions are presented in Figs. 8.3 and 8.4 for two values of $\gamma-\beta$ (the numerals at the curves). It can be seen from the figures that the two methods for obtaining the coupling functions give substantially different results.

It seems to us that the results obtained by the second semi-empirical method are more realistic in that this method gives satisfactory results for the earth's atmosphere. The median energy found by the second method is $(3-4) \times 10^3 \text{ GeV}$ for Venus and $(2-3) \times 10^3 \text{ GeV}$ for Jupiter. It should be noted that more detailed



calculations of the properties of the secondary components require that the muon decays should be more strictly taken into account (this effect for Venus is of little significance, but in the case of Jupiter the inclusion of the decay-effect will result in a shift of the coupling function to range of somewhat higher energies).

As for the expected magnetic effects, it was shown in Dorman et al. (1979b) based on the data on the magnetic moments of Venus and Jupiter (Ness, 1978), that the vertical magnetic cutoff rigidities are about $10^{-3} GV$ and 2,400 GV at the magnetic equators of Venus and Jupiter, respectively. It follows from these data that the latitude magnetic effect is absent on Venus and must be very significant on Jupiter: the muon intensity on the planetary surface should decrease by a factor of about 2 from pole to magnetic equator (see curve II in the lower panel of Fig. 8.4).

Conclusion and Problems

Mostly, each section or chapter concludes with a discussion and a summary of the main obtained results of the considered problems and how to further develop these problems. Thus, it is not necessary to give detailed conclusions here. Therefore, I give one general conclusion and mention several problems which seem to me to be important to resolve in the near future.

General Conclusion

The discovery of the cosmic rays (CR) in 1912 by Austrian scientist Victor Hess will see its 100th anniversary in a few years. The importance of this discovery was not recognized for many years. It was only in 1936 that Victor Hess received the Nobel Prize in Physics together with Karl Anderson for the discovery of the CR positron – the first anti-particle. After the discovery of the CR it was supposed that CRs are high-energy, gamma-quanta (which explains why Nobel Laureate Robert Millikan in 1928 proposed to call this radiation arriving from space cosmic rays, and this nomination was generally accepted for many years, up to the present time). Only in the 1930s, after the discovery of CR geomagnetic effects, it became clear that primary CRs are charged particles and that the sign of charge is mostly positive. The first explanation of geomagnetic effects was based on the dipole approximation of the geomagnetic field and only many years later after detail investigations of CR geomagnetic effects (and especially CR equator) it became clear that it is necessary to also take into account higher harmonics of the main geomagnetic field, just as magnetic fields from magnetospheric currents. Perhaps the highest achievement in this direction is the development in the last two decades of complicated magnetospheric models (mostly by N. Tsyganenko and his colleagues) which made it possible to calculate expected CR cutoff rigidities, asymptotic directions, and accepted cones more accurately. It is important that this research is extended for other planets and satellites. The following is a list of problems we consider are important to solve.

Problem 1

We now have a huge body of data from CR planetary surveys on ships, trains, tracks, planes, balloons, and satellites made during 5–6 solar cycles for different CR secondary components. While in the past inexact cutoff rigidities were used, it is now possible to determine effective cutoff rigidities by using appropriate magnetospheric models depending on geomagnetic activity not only for the present time, but also for the past. It is important that these calculations are made for the past planetary CR surveys as a new, more exact interpretation of experimental data can be obtained based on these results. In that case a lot of past CR survey data may be effectively used again for checking magnetospheric models and obtaining other information (determining integral multiplicities and coupling functions, normalization of worldwide CR stations, long-term CR time variations, etc.).

Problem 2

It is important to continue the tradition of regular CR surveys at sea level and organize new planetary surveys between the Arctic and Antarctica for standard CR detectors including measurements of different neutron multiplicities.

Problem 3

It will be very important to develop fully automatically workable CR stations and put them on cargo and passenger ships for continued planetary surveys. Each moving CR station will give information in real-time scale not only about CR intensity of different secondary components (total neutron component and different multiplicities, muon component from different directions, etc.), but also about exact geographic coordinates and direction of ship, atmospheric pressure and temperature, sea-state amplitude, and velocity of wind. In that case we will have not only continuous unique information on CR planetary distributions for each moment of time, but also very important information for using global-spectrographic methods for effective investigations of different types of CR variations (i.e., a lot of "white spots" in CR world distribution from stationary CR stations will be closed). The extended network of stationary and moving CR stations may be much more effective also for problems of space weather (e.g., forecasting of dangerous magnetic storms by analyzing space-time galactic CR distribution and great radiation hazards from solar CRs).

Problem 4

It will be also very important to develop fully automatically workable small and light CR stations for regular aircraft lines on an altitude of about 10 km for continued planetary surveys. Each moving aircraft CR station will give information in real-time scale not only about CR intensity of different secondary components, but also about exact geographic coordinates and altitudes of aircraft. We will then have continuous information on CR planetary distributions for each moment of time. We will also have important information for using global spectrographic method for effective investigations of different types of CR variations, and by analyzing space-energy-time of CR distribution it will be possible to organize continuous monitoring and forecasting of dangerous space weather phenomena.

Problem 5

It is important to use CR data of low-altitude satellite surveys conducted in the past to obtain CR planetary distribution and compare them with expected results from modern magnetospheric models. We also need to continue to obtain and use these data in the future not only for checking magnetospheric models, but also for investigating CR variations and space weather problems.

Problem 6

It is important to continue the tradition of M.A. Shea and D.F. Smart to calculate for each 5 years the planetary distributions of CR cutoff rigidities for vertical direction. It is equally important to extend the traditional information with data on cutoff rigidities for oblique directions also, and calculate apparent cutoff rigidities for all CR stations and CR latitude surveys.

Problem 7

It is necessary to calculate CR asymptotic directions and acceptance cones for each CR station at different epochs in the frame of modern magnetospheric models depending on geomagnetic activity and properties of solar wind. This will make it possible to use more effectively and exactly the global spectrographic method for analyzing data from worldwide network of CR stations.

Problem 8

It is necessary to continue calculations of transmissivity functions for all CR stations that are dependent on solar wind properties and magnetic activity in the frame of modern magnetospheric models.

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Appendix

Table	anonquikse 1.ce:		IOF VELICA	Therease	ss at the tor	aiver Julie	I HEL OF STAL	HOILS (ACCI	T OI BUINIC	NUTILIALI EL A	u., 1900)			
No.	Station	Angle						Rigidity	y (GV)					
			1.0	1.27	1.45	1.60	1.88	2.20	2.63	3.15	4.37	5.74	7.73	10.5
-	Apatity	$\Lambda,^{\circ}$	-10.0	-9.4	-6.5	-3.3	0.0	4.4	10.4	12.7	22.1	26.4	35.1	37.2
		°,	141.9	119.6	110.2	104.9	98.8	92.4	88.3	84.4	<i>0.17</i>	77.5	72.6	68.5
2	Alma-Ata	$\Lambda,^{\circ}$	I	I	I	I	I	I	I	I	I	I	7.6	-12.7
		ф, Ф	I	I	I	I	I	I	I	I	I	I	240.7	187.0
ю	Vostok	$\mathbf{v},^{\circ}$	-62.6	-63.9	-64.5	-65.7	-66.8	-67.1	-67.0	-69.4	-70.6	-69.5	-72.0	-73.3
		°,	36.4	38.0	38.5	37.6	39.4	42.6	41.7	42.5	47.9	45.5	55.1	46.2
4	Irkutsk	$\Lambda,^{\circ}$	I	I	I	I	I	I	I	I	5.6	-18.4	-12.3	-9.0
		°,	I	I	I	I	I	I	I	I	283.3	211.2	175.8	162.8
5	Moscow	$^{\circ}, ^{\circ}$	I	I	I	I	I	I	-4.5	0.9	-11.2	-6.5	3.5	5.7
		ф,°	I	I	I	I	I	I	268.9	177.2	127.4	108.0	91.1	84.6
9	Mirny	$^{\circ},^{\circ}$	-22.6	-26.3	-27.9	-29.1	-32.0	-34.2	-34.8	-38.6	-42.6	-42.2	-47.6	-50.3
		°,	85.4	85.3	85.1	83.6	83.4	84.8	84.4	83.2	85.6	83.6	87.1	81.3
7	Tixie	$\Lambda,^{\circ}$	-20.1	-12.6	-7.8	-5.2	0.0	5.8	10.7	15.2	24.1	28.6	36.3	39.6
		°,	201.1	185.4	180.0	176.0	172.0	168.9	167.0	164.1	161.5	161.2	159.7	157.9
8	Tbilisi	$^{\circ},^{\circ}$	I	I	I	I	I	I	I	I	I	I	14.4	-9.1
		°,	Ι	Ι	I	Ι	I	Ι	I	Ι	Ι	Ι	217.8	158.8
6	Heiss Island	$\Lambda,^{\circ}$	34.6	39.1	41.4	42.3	45.1	48.0	49.8	52.3	57.1	58.7	63.1	65.9
		°,	105.8	104.1	103.6	102.9	101.6	101.4	101.2	99.1	98.7	97.3	98.6	94.1
10	Cape Schmidt	$\Lambda,^{\circ}$	-29.2	-24.7	-19.8	-17.2	-12.0	-5.3	0.4	4.5	14.9	19.2	28.7	31.1
		°, (Ф	155.5	231.7	223.4	219.7	214.0	209.3	207.2	203.8	200.8	201.5	199.5	197.0
11	Yakutsk	$^{\circ},^{\circ}$	I	I	I	I	-10.1	-9.0	-23.0	-22.7	-12.1	-4.2	8.5	12.4
		ф [`]	I	I	I	I	40.9	269.5	232.1	212.9	187.9	180.4	171.9	167.6
12	Simfe-ropol	$\mathbf{\Lambda},^{\circ}$	I	I	I	Ι	Ι	I	Ι	Ι	Ι	-20.2	-3.1	-14.6
		ф`,	I	I	I	I	Ι	I	I	I	I	299.3	148.4	122.8
13	Sverd-lovsk	$^{\circ},^{\circ}$	I	I	I	I	Ι	I	9.2	-4.9	-11.7	-6.6	5.0	8.5
		°, ф	I	I	I	I	I	I	243.0	190.6	143.9	127.8	112.5	105.6

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Appendix to Chapter 3

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Table

No.	Angle						R	igidity (GV	(,					
		13.2	14.9	17.0	19.4	22.9	26.0	30.0	34.5	39.7	45.6	52.5	60.3	69.4
_	$\Lambda,^{\circ}$	39.1	41.0	43.4	46.3	49.8	52.5	55.3	57.7	59.7	61.4	62.9	64.0	64.9
	°,	69.5	70.5	71.4	72.0	72.0	71.5	70.4	68.8	66.8	64.5	62.1	59.5	56.9
2	v ,°	-17.6	-14.2	-8.1	-1.1	7.5	13.5	19.3	24.1	28.1	31.4	34.0	36.1	37.8
	°,	162.7	152.7	144.5	139.3	132.1	128.1	123.8	119.8	116.0	112.2	108.7	105.1	102.0
б	$\Lambda,^{\circ}$	-70.9	-69.8	-69.0	-68.7	-68.8	-69.2	-69.8	-70.4	-71.1	-71.8	-72.5	-73.2	-73.8
	ф, о	46.6	50.0	54.9	60.0	66.4	70.9	75.6	79.6	83.2	86.3	89.2	91.5	92.2
4	$\mathbf{v}^{,\circ}$	-3.2	1.4	7.3	13.3	20.6	25.7	30.7	35.0	38.6	41.5	43.9	45.8	47.3
	°,	157.8	155.9	154.0	152.3	150.1	148.1	145.6	143.0	140.1	137.2	134.2	131.2	128.4
5	°,∿	10.3	14.1	18.7	23.6	26.3	33.6	37.8	41.3	44.3	46.7	48.7	50.3	51.5
	°,	83.4	83.0	82.5	81.7	80.3	78.3	76.6	74.3	71.6	68.9	66.0	63.2	60.4
9	<u>о</u> , v	-48.6	-47.9	-47.7	-48.1	-49.2	-50.4	-51.8	-53.3	-54.8	-66.2	-57.4	-68.5	-59.6
	ф, о	80.6	81.9	84.1	86.5	89.4	95.4	93.4	94.6	95.7	95.8	96.8	97.1	97.2
7	$\mathbf{v}^{,\circ}$	42.3	44.3	46.8	49.5	53.1	55.6	58.3	60.6	62.6	64.3	65.8	68.0	67.8
	°,	159.4	160.9	161.9	162.5	163.2	163.1	162.5	161.2	159.9	158.0	155.9	153.7	151.4
8	$^{\circ},^{\circ}$	-16.2	-13.0	-7.0	0.0	8.3	14.0	19.6	24.3	28.1	31.1	33.6	35.5	37.0
	°,	133.0	122.5	113.8	107.8	100.8	96.5	92.0	87.7	83.7	79.9	76.2	72.7	69.5
6	$^{\circ},^{\circ}$	66.7	67.4	68.3	6.69	70.9	72.1	73.5	74.7	75.7	76.7	77.5	78.2	78.7
	°,	93.4	94.1	95.1	96.0	96.9	97.0	96.6	95.7	94.7	92.4	90.1	88.1	85.6
10	$\Lambda,^{\circ}$	33.1	35.2	38.0	41.1	45.2	48.2	51.4	54.2	56.6	58.7	60.5	62.0	63.3
	ф [°]	199.4	201.1	203.1	204.7	206.1	206.7	206.8	206.4	205.5	204.3	202.8	201.1	199.5
11	v,°	16.8	20.3	24.6	29.3	35.0	39.1	43.3	46.8	49.8	52.3	54.4	56.0	57.4
	¢,°	168.2	168.8	169.5	169.7	169.6	168.8	167.5	165.8	163.8	161.4	158.9	156.3	153.6
12	$\Lambda,^{\circ}$	-12.7	-8.0	1.6	5.2	13.2	18.6	24.0	28.4	32.0	34.9	37.2	39.0	40.5
	ф` °	107.6	101.2	95.7	91.3	86.5	83.0	79.3	75.5	71.8	68.2	64.6	61.3	58.3
13	°,'	12.7	16.1	20.3	24.8	30.4	34.4	38.4	41.9	44.8	47.2	49.2	50.8	52.2
	°. Ф	104.4	104.0	103.6	103.0	101.8	100.5	98.7	96.5	94.2	91.7	89.0	86.5	83.6

(Continued)

No.	Angle						Ri	igidity (GV	(
		79.8	91.8	106	121	140	161	185	212	244	281	323	371	427
_	$\Lambda,^{\circ}$	65.6	66.1	66.5	66.8	67.0	67.2	67.3	67.4	67.5	67.5	67.5	67.6	67.3
	°,	54.4	51.9	49.8	47.9	46.1	44.3	43.0	41.8	40.6	39.7	38.9	38.0	37.4
2	$^{\circ},^{\circ}$	39.1	40.1	40.8	41.5	41.9	42.2	42.3	42.6	42.8	42.9	43.0	43.1	43.1
	°,	99.1	96.5	94.1	92.0	90.1	88.4	86.8	85.6	84.5	83.3	82.6	81.7	81.1
б	$^{\circ},^{\circ}$	-74.3	-74.8	-75.2	-75.6	-76.0	-76.3	-76.5	-76.8	-77.0	-77.2	-77.3	-77.5	-77.6
	°,	95.4	96.9	98.3	99.4	100.5	101.3	102.1	102.7	103.3	103.8	104.2	104.6	104.9
4	v,°	48.5	49.5	50.2	50.7	51.2	51.5	51.7	51.9	52.1	52.2	52.2	52.3	52.3
	°,	125.7	123.1	120.9	118.9	116.9	115.4	113.9	112.7	111.4	110.5	109.6	108.6	108.2
5	v,°	52.5	53.3	53.9	52.7	54.6	54.8	55.0	55.1	55.3	55.3	55.4	55.4	55.4
	°,	57.9	55.5	53.2	47.5	49.6	48.0	46.6	45.4	44.4	43.4	42.6	41.9	41.3
9	v,°	-60.5	-61.3	-62.0	-62.6	-67.2	-63.6	-64.0	-64.2	-64.6	-64.9	-65.1	-65.3	-65.5
	ф [`]	97.1	96.1	96.7	96.5	96.2	95.9	95.6	95.4	95.2	95.0	94.7	94.5	94.4
7	°, `V	68.6	69.3	69.8	70.2	70.5	70.7	70.9	71.0	71.1	71.2	71.3	71.4	71.4
	°,	149.3	147.0	145.0	143.2	141.5	139.8	138.5	137.2	136.2	135.3	134.4	133.7	133.1
8	$^{\circ},^{\circ}$	38.2	39.1	39.8	40.2	40.7	41.0	41.2	41.3	41.4	41.5	41.6	41.6	41.7
	°,	66.6	63.9	61.4	59.5	57.6	55.8	54.6	53.2	52.1	51.0	50.2	49.4	48.8
6	$^{\circ},^{\circ}$	79.1	79.5	79.8	80.0	80.1	80.3	80.4	80.6	80.5	80.5	80.5	80.5	80.6
	°,	83.0	80.5	77.5	75.8	73.6	71.7	70.0	68.4	67.1	66.0	65.0	63.9	61.3
10	$^{\circ},^{\circ}$	64.3	65.1	65.9	66.4	66.8	67.2	67.5	67.8	68.0	68.1	68.3	68.4	68.5
	°,	197.7	195.9	194.1	192.6	191.2	189.8	188.6	187.4	186.5	185.4	184.8	184.1	183.4
11	$^{\circ},^{\circ}$	58.5	59.3	59.9	60.4	60.8	61.1	61.3	61.5	61.6	61.7	61.8	61.5	61.9
	ф [`]	151.1	148.9	146.5	144.5	142.7	141.0	139.6	138.3	137.3	136.7	135.3	134.6	133.9
12	°,∙	41.6	42.4	43.0	43.5	43.9	44.1	44.3	44.4	44.5	44.6	44.7	44.7	44.7
	ф` °	55.5	52.8	50.4	48.5	46.5	44.9	43.4	42.3	41.1	40.2	39.4	38.6	38.0
13	$^{\circ},^{\circ}$	53.2	54.0	54.6	55.1	55.5	55.8	56.0	56.2	56.4	56.4	56.5	56.5	56.6
	°, ¢	81.3	79.0	76.8	75.0	73.2	71.7	70.4	69.1	68.1	67.1	66.3	65.7	64.9

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Table A3.1 (Continued)

No.	Angle			Rigidit	y (GV)		
		491	565	650	747	859	938
_	$\Lambda,^{\circ}$	67.6	67.6	67.6	67.6	67.6	67.6
	°,	36.9	36.5	36.0	35.6	35.3	35.1
2	N,°	43.2	43.1	43.2	43.2	43.2	43.2
	ф,	80.6	80.0	79.6	79.2	78.9	78.7
3	v ,°	-77.7	-77.8	-77.9	-78.0	-78.0	-78.0
	ф`,	105.1	105.4	105.6	105.8	105.9	106.1
4	$^{\circ}, ^{\circ}$	52.4	52.4	52.4	52.4	52.4	52.4
	Ф,	107.6	107.6	106.7	106.2	106.0	105.7
5	$\mathbf{v},^{\circ}$	55.4	55.4	55.5	55.5	55.5	55.5
	ф, о	40.7	40.3	39.9	39.4	39.2	38.9
9	$\mathbf{\Lambda},^{\circ}$	-65.6	-65.7	-65.8	-65.9	-66.0	-66.1
	ф, °	94.2	94.1	93.9	93.8	93.7	93.6
7	$\mathbf{v},^{\circ}$	71.5	71.5	71.5	71.5	71.5	71.5
	ф, °	132.4	131.9	131.5	131.2	130.9	130.5
8	$^{\circ},^{\circ}$	41.7	41.7	41.7	41.7	41.7	41.7
	ф, °	48.3	47.8	47.4	47.0	46.6	46.4
6	$^{\circ}, ^{\circ}$	80.6	80.6	80.6	80.6	80.6	80.6
	ф, °	62.5	61.9	62.0	60.8	60.5	60.1
10	°,∘	68.5	68.6	68.6	68.7	68.7	68.8
	ф, °	183.0	182.5	182.1	181.6	181.3	181.1
11	°,∘	61.9	61.9	62.0	62.0	62.0	62.0
	ф,°	133.3	132.9	132.4	132.0	131.7	131.4
12	$^{\circ},^{\circ}$	44.7	44.7	44.8	44.8	44.7	44.7
	ф,°	37.5	36.9	36.6	36.2	35.8	35.6
13	$^{\circ},^{\circ}$	56.6	56.6	56.6	56.7	56.7	56.7
	°, Ф	64.4	64.0	63.6	63.2	62.9	62.6

Table A3.1 (Continued)

Geographic					Geo	graphic l	ongitud	e (E)				
latitude	0	15	30	45	60	75	90	105	120	135	150	165
85	0.01	0.02	0.02	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.03	0.03
80	0.03	0.05	0.07	0.09	0.10	0.12	0.13	0.14	0.12	0.13	0.12	0.09
75	0.12	0.15	0.21	0.23	0.26	0.28	0.28	0.29	0.31	0.29	0.29	0.27
70	0.29	0.37	0.44	0.49	0.52	0.56	0.56	0.60	0.64	0.64	0.62	0.61
65	0.60	0.73	0.88	0.93	1.00	1.01	1.04	1.10	1.17	1.21	1.22	1.19
60	1.14	1.37	1.50	1.65	1.69	1.74	1.81	1.89	2.01	2.06	2.16	2.10
55	2.02	2.24	2.54	2.61	2.74	2.78	2.92	2.99	3.14	3.41	3.40	3.24
50	3.06	3.52	3.88	4.05	4.15	4.28	4.39	4.58	4.76	4.98	4.95	4.71
45	4.71	5.18	5.42	5.62	5.76	5.98	6.18	6.34	6.64	6.94	6.95	6.47
40	6.64	7.37	7.57	7.81	8.23	8.75	9.16	9.39	9.68	9.94	9.80	9.03
35	9.49	9.86	9.95	10.61	11.10	11.65	11.66	11.84	12.00	12.07	11.59	10.76
30	11.24	11.76	12.13	12.64	13.31	14.07	14.44	14.51	14.35	14.04	13.55	12.88
25	12.99	13.59	14.06	14.46	14.99	15.56	15.91	15.88	15.58	15.12	14.55	13.92
20	14.01	14.56	14.99	15.44	16.01	16.59	16.92	16.84	16.45	15.91	15.31	14.72
15	14.51	15.05	15.52	16.01	16.61	17.20	17.52	17.42	17.00	16.44	15.87	15.34
10	14.66	15.16	15.65	16.18	16.81	17.40	17.71	17.63	17.24	16.72	16.21	15.77
5	14.49	14.92	15.41	15.98	16.62	17.20	17.52	17.50	17.19	16.74	16.32	15.98
0	14.03	14.37	14.84	15.43	16.08	16.63	16.95	17.01	16.82	16.49	16.17	15.95
-5	13.34	13.55	13.98	14.57	15.20	15.70	16.01	16.16	16.12	15.92	15.73	15.64
-10	12.45	12.52	12.89	13.46	14.02	14.43	14.71	14.95	15.04	14.99	14.93	14.98
-15	11.09	11.16	11.53	12.02	12.39	12.74	12.99	13.26	13.44	13.58	13.68	13.91
-20	9.55	9.38	9.70	10.00	10.28	10.30	10.36	10.60	10.96	10.77	10.94	12.02
-25	8.07	7.76	7.90	8.14	8.07	7.60	7.11	7.19	7.60	7.91	8.64	9.66
-30	6.85	6.22	6.10	5.91	5.68	5.37	5.12	5.08	5.20	5.54	5.98	6.73
-35	5.66	4.83	4.59	4.41	4.24	3.91	3.36	3.28	3.44	3.72	4.26	4.89
-40	4.58	3.92	3.59	3.32	2.95	2.63	2.18	2.02	2.09	2.28	2.70	3.31
-45	3.74	3.13	2.70	2.38	2.06	1.66	1.35	1.17	1.14	1.27	1.55	2.05
-50	3.15	2.44	2.07	1.74	1.37	1.04	0.76	0.60	0.55	0.64	0.83	1.15
-55	2.47	1.89	1.53	1.19	0.88	0.59	0.39	0.28	0.23	0.27	0.38	0.60
-60	1.90	1.44	1.10	0.80	0.55	0.36	0.19	0.11	0.07	0.09	0.16	0.27
-65	1.44	1.04	0.77	0.51	0.32	0.18	0.07	0.03	0.01	0.02	0.04	0.12
-70	0.99	0.73	0.51	0.32	0.19	0.08	0.03	0.01	0.00	0.00	0.01	0.04
-75	0.64	0.49	0.32	0.21	0.12	0.05	0.01	0.00	0.00	0.00	0.00	0.01
-80	0.39	0.28	0.21	0.14	0.07	0.04	0.01	0.01	0.00	0.00	0.00	0.01
-85	0.20	0.18	0.13	0.11	0.07	0.05	0.04	0.03	0.02	0.02	0.03	0.04

Table A3.2 Five by 15 degree world grids of trajectory-derived effective vertical cutoff rigidities (in GV) for epoch 1955.0 (According to Shea et al., 1968)

(Continued)
Geographic					Geo	graphic l	ongitud	e (E)				
latitude	180	195	210	225	240	255	270	285	300	315	330	345
1	2	3	4	5	6	7	8	9	10	11	12	13
85	0.02	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
80	0.07	0.05	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
75	0.22	0.16	0.09	0.05	0.02	0.00	0.00	0.00	0.00	0.01	0.03	0.06
70	0.51	0.38	0.26	0.14	0.06	0.02	0.01	0.01	0.02	0.05	0.10	0.19
65	1.03	0.84	0.59	0.35	0.20	0.09	0.05	0.04	0.07	0.14	0.29	0.43
60	1.84	1.48	1.06	0.71	0.43	0.24	0.16	0.14	0.19	0.34	0.55	0.85
55	2.95	2.34	1.80	1.27	0.80	0.50	0.36	0.32	0.41	0.66	1.06	1.53
50	4.36	3.62	2.85	2.08	1.45	0.96	0.71	0.63	0.79	1.19	1.81	2.58
45	5.63	4.92	4.22	3.20	2.42	1.73	1.27	1.14	1.35	1.98	2.97	4.01
40	8.05	6.60	5.60	4.68	3.75	2.88	2.14	1.87	2.10	2.96	4.50	5.65
35	9.63	9.21	7.87	6.36	6.38	4.35	3.23	2.82	3.11	4.50	6.06	8.43
30	11.88	10.78	9.90	9.11	7.35	5.83	4.59	3.93	4.24	5.88	8.91	10.46
25	13.29	12.71	12.14	11.37	10.11	8.21	6.24	5.15	5.80	8.44	10.92	12.17
20	14.16	13.68	13.25	12.70	11.89	10.46	8.09	6.99	7.67	10.38	12.40	13.32
15	14.86	14.44	14.08	13.64	13.03	11.84	9.79	7.63	9.26	12.11	13.18	13.90
10	15.37	15.01	14.68	14.31	13.82	12.97	11.71	10.80	11.68	12.87	13.62	14.16
5	15.6S	15.37	15.06	14.74	14.34	13.75	12.90	12.33	12.71	13.30	13.79	14.13
0	15.75	15.51	15.24	14.95	14.61	14.17	13.61	13.15	13.14	13.47	13.71	13.84
-5	15.55	15.40	15.19	14.94	14.66	14.31	13.86	13.44	13.31	13.42	13.43	13.34
-10	15.05	15.02	14.90	14.74	14.53	14.25	13.88	13.48	13.26	13.17	12.97	12.66
-15	14.17	14.34	14.37	14.33	14.21	14.01	13.71	13.33	13.02	12.76	12.33	11.62
-20	12.87	13.27	13.57	13.69	13.70	13.61	13.38	13.02	12.64	12.19	11.44	10.43
-25	10.37	11.22	12.11	12.80	13.01	13.05	12.91	12.58	12.11	11.45	10.47	9.03
-30	7.96	9.46	9.54	10.62	12.09	12.33	12.32	12.01	11.44	10.62	9.28	7.73
-35	5.72	6.63	7.93	9.24	9.61	11.40	11.60	11.37	10.63	9.60	8.03	6.73
-40	4.16	4.91	5.59	6.75	8.38	9.64	10.70	10.41	9.73	8.54	7.15	5.93
-45	2.75	3.42	4.31	4.92	5.92	7.87	9.30	9.33	8.60	7.67	6.54	4.79
-50	1.67	2.28	2.97	3.80	4.53	5.61	7.19	8.01	7.07	6.58	5.10	3.96
-55	0.95	1.41	1.94	2.65	3.40	4.32	5.12	5.52	5.50	4.96	4.02	3.27
-60	0.49	0.80	1.24	1.74	2.32	3.07	3.89	4.26	4.24	3.92	3.29	2.50
-65	0.23	0.45	0.73	1.12	1.55	2.08	2.65	2.90	2.94	2.75	2.37	1.86
-70	0.10	0.23	0.41	0.66	0.98	1.31	1.64	1.89	1.97	1.87	1.60	1.31
-75	0.05	0.12	0.24	0.38	0.56	0.77	0.94	1.07	1.17	1.11	1.00	0.83
-80	0.04	0.08	0.15	0.22	0.32	0.42	0.51	0.59	0.62	0.60	0.54	0.48
-85	0.05	0.07	0.11	0.15	0.18	0.20	0.24	0.27	0.28	0.28	0.28	0.23

Table A3.2 (Continued)

Geographic						Geogra	phic lo	ngitude					
latitude	0	15	30	45	60	75	90	105	120	135	150	165	180
80	0.02	0.04	0.06	0.08	0.09	0.10	0.11	0.11	0.11	0.11	0.10	0.09	0.06
75	0.10	0.14	0.18	0.20	0.23	0.24	0.25	0.26	0.28	0.28	0.27	0.24	0.20
70	0.26	0.33	0.40	0.45	0.48	0.53	0.52	0.56	0.58	0.59	0.59	0.57	0.47
65	0.57	0.71	0.80	0.87	0.92	0.94	1.00	1.02	1.09	1.15	1.17	1.12	0.99
60	1.11	1.30	1.45	1.58	1.65	1.69	1.73	1.78	1.92	2.03	2.10	2.03	1.75
55	2.01	2.17	2.40	2.59	2.66	2.72	2.77	2.94	3.05	3.27	3.27	3.13	2.87
50	3.11	3.52	3.83	3.97	4.11	4.23	4.35	4.43	4.69	4.85	4.92	4.68	4.24
45	4.71	5.15	5.34	5.48	5.66	5.84	6.09	6.27	6.50	6.80	6.82	6.33	5.54
40	6.62	7.26	7.54	7.77	8.12	8.61	9.00	9.21	9.48	9.82	9.69	8.93	7.88
35	9.43	9.82	10.02	10.47	11.06	11.41	11.46	11.63	11.85	11.90	11.47	10.58	9.53
30	11.22	11.71	12.12	12.60	13.22	13.97	14.30	14.35	14.21	13.92	13.43	12.73	11.69
25	13.03	13.59	14.06	14.48	14.98	15.49	15.79	15.75	15.46	15.01	14.44	13.79	13.13
20	14.06	14.58	15.05	15.51	16.04	16.56	16.83	16.73	16.35	15.82	15.21	14.59	14.00
15	14.58	15.11	15.62	16.13	16.68	17.20	17.45	17.33	16.92	16.37	15.78	15.22	14.71
10	14.72	15.24	15.77	16.31	16.90	17.41	17.66	17.56	17.19	16.67	16.13	15.66	15.24
5	14.52	15.00	15.52	16.08	16.70	17.22	17.48	17.44	17.14	16.70	16.25	15.89	15.57
0	14.00	14.40	14.90	15.48	16.11	16.64	16.93	16.96	16.77	16.43	16.11	15.88	15.67
-5	13.23	13.52	13.96	14.54	15.18	15.69	16.01	16.14	16.06	15.85	15.66	15.57	15.50
-10	12.28	12.42	12.79	13.35	13.95	14.41	14.73	14.95	14.98	14.90	14.84	14.92	15.02
-15	10.89	11.03	11.35	11.79	12.26	12.76	13.06	13.31	13.38	13.46	13.60	13.86	14.14
-20	9.37	9.23	9.45	9.81	10.26	10.32	10.48	10.75	10.83	10.58	10.85	12.00	12.84
-25	7.79	7.67	7.80	7.98	7.96	7.58	7.29	7.34	7.60	7.93	8.64	9.65	10.30
-30	6.64	6.16	5.95	5.73	5.56	5.30	5.12	5.20	5.20	5.48	6.00	6.66	7.94
-35	5.43	4.79	4.47	4.31	4.18	3.84	3.41	3.33	3.51	3.70	4.22	4.98	5.68
-40	4.39	3.82	3.53	3.33	2.88	2.54	2.19	2.08	2.07	2.26	2.63	3.31	4.13
-45	3.59	3.02	2.60	2.40	2.04	1.57	1.30	1.14	1.14	1.26	1.51	2.01	2.67
-50	3.00	2.37	1.99	1.70	1.33	0.97	0.71	0.55	0.56	0.63	0.79	1.15	1.62
-55	2.39	1.84	1.49	1.17	0.82	0.56	0.37	0.26	0.22	0.26	0.37	0.61	0.94
-60	1.81	1.33	1.03	0.75	0.51	0.30	0.16	0.09	0.07	0.09	0.15	0.27	0.48
-65	1.34	0.99	0.73	0.49	0.30	0.15	0.06	0.00	0.00	0.00	0.03	0.11	0.23
-70	0.93	0.68	0.48	0.30	0.17	0.08	0.00	0.00	0.00	0.00	0.00	0.02	0.10
-75	0.59	0.43	0.30	0.19	0.10	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.04
-80	0.37	0.27	0.19	0.12	0.07	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.02

Table A3.3 The $5^{\circ} \times 15^{\circ}$ world grids of trajectory-derived effective vertical cutoff rigidities for epoch 1965.0 (According to Shea and Smart, 1975b)

Geographic					Ge	ographi	e longitu	de				
latitude	195	210	225	240	255	270	285	300	315	330	345	360
80	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
75	0.14	0.09	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.10
70	0.35	0.24	0.13	0.06	0.00	0.00	0.00	0.00	0.04	0.10	0.17	0.26
65	0.75	0.52	0.31	0.17	0.09	0.04	0.04	0.07	0.14	0.26	0.41	0.57
60	1.38	1.01	0.68	0.39	0.23	0.15	0.14	0.20	0.35	0.56	0.84	1.11
55	2.27	1.74	1.21	0.80	0.49	0.35	0.33	0.43	0.68	1.08	1.53	2.01
50	3.46	2.79	2.02	1.38	0.94	0.70	0.66	0.81	1.29	1.88	2.57	3.11
45	4.89	4.17	3.16	2.40	1.72	1.28	1.13	1.43	2.04	3.06	4.15	4.71
40	6.43	5.50	4.63	3.67	2.81	2.06	1.91	2.24	3.22	4.66	5.70	6.62
35	9.01	7.74	6.24	5.23	4.21	3.21	2.88	3.29	4.65	6.46	8.53	9.43
30	10.55	9.70	8.95	7.13	5.71	4.54	4.09	4.57	6.36	9.33	10.47	11.22
25	12.53	11.94	11.17	9.92	8.02	6.13	5.28	6.09	8.93	11.14	12.34	13.03
20	13.50	13.04	12.51	11.67	10.09	7.89	6.93	8.22	10.88	12.60	13.45	14.06
15	14.27	13.91	13.48	12.81	11.53	9.64	7.91	10.15	12.35	13.33	14.02	14.58
10	14.86	14.54	14.19	13.67	12.77	11.58	11.01	12.00	13.00	13.72	14.24	14.72
5	15.26	14.96	14.64	14.23	13.62	12.77	12.43	12.76	13.35	13.82	14.14	14.52
0	15.43	15.16	14.86	14.51	14.05	13.49	13.06	13.10	13.44	13.66	13.77	14.00
-5	15.34	15.12	14.87	14.57	14.19	13.71	13.29	13.20	13.31	13.29	13.18	13.23
-10	14.98	14.84	14.66	14.43	14.12	13.71	13.29	13.08	12.99	12.75	12.40	12.28
-15	14.31	14.30	14.23	14.09	13.86	13.51	13.10	12.79	12.52	12.03	11.41	10.89
-20	13.23	13.49	13.58	13.57	13.44	13.16	12.75	12.37	11.90	11.07	10.05	9.37
-25	11.20	12.00	12.68	12.86	12.87	12.68	12.29	11.81	11.09	10.03	8.75	7.79
-30	9.44	9.43	10.54	11.94	12.15	12.09	11.73	11.07	10.16	8.90	7.40	6.64
-35	6.60	7.87	9.14	9.46	11.23	11.37	10.99	10.38	9.18	7.66	6.31	5.43
-40	4.81	5.57	6.59	8.24	9.70	10.49	10.08	9.31	8.02	6.85	5.61	4.39
-45	3.40	4.27	4.88	5.90	7.87	9.11	9.03	8.16	7.35	6.03	4.51	3.59
-50	2.19	2.95	3.67	4.50	5.61	7.13	7.80	7.34	6.09	4.75	3.73	3.00
-55	1.35	1.91	2.55	3.26	4.24	5.04	5.40	5.28	4.66	3.88	3.12	2.39
-60	0.77	1.20	1.66	2.26	3.02	3.82	4.09	4.09	3.65	3.03	2.37	1.81
-65	0.43	0.70	1.04	1.46	1.96	2.58	2.77	2.80	2.55	2.18	1.70	1.34
-70	0.22	0.39	0.62	0.89	1.24	1.55	1.79	1.84	1.71	1.44	1.20	0.93
-75	0.11	0.22	0.36	0.54	0.69	0.90	1.00	1.09	1.07	0.95	0.76	0.59
-80	0.07	0.13	0.20	0.29	0.38	0.46	0.53	0.57	0.55	0.50	0.44	0.37

Table A3.3 (Continued)

Geographic						Geogra	phic lo	ngitude					
latitude	0	15	30	45	60	75	90	105	120	135	150	165	180
80	0.02	0.04	0.06	0.09	0.09	0.10	0.10	0.11	0.11	0.11	0.10	0.08	0.06
75	0.10	0.14	0.18	0.20	0.23	0.25	0.25	0.26	0.27	0.28	0.26	0.24	0.20
70	0.26	0.34	0.41	0.47	0.49	0.51	0.52	0.55	0.59	0.60	0.62	0.56	0.47
65	0.58	0.72	0.80	0.89	0.93	0.97	1.01	1.03	1.12	1.19	1.20	1.13	0.95
60	1.14	1.34	1.46	1.57	1.61	1.67	1.73	1.82	1.95	2.05	2.05	1.99	1.75
55	1.94	2.20	2.47	2.61	2.68	2.78	2.85	2.92	3.12	3.31	3.35	3.15	2.88
50	3.21	3.54	3.81	3.97	4.14	4.27	4.36	4.37	4.69	4.93	4.92	4.67	4.27
45	4.77	5.12	5.36	5.51	5.73	5.90	6.11	6.29	6.57	6.86	6.86	6.33	5.59
40	6.75	7.27	7.48	7.70	8.19	8.73	9.14	9.29	9.49	9.89	9.74	8.95	7.86
35	9.54	9.89	10.10	10.53	11.15	11.44	11.52	11.71	11.93	12.04	11.55	10.60	9.49
30	11.30	11.71	12.13	12.67	13.34	14.07	14.37	14.40	14.26	13.95	13.44	12.72	11.65
25	13.10	13.64	14.10	14.53	15.06	15.58	15.85	15.79	15.49	15.03	14.44	13.76	13.07
20	14.11	14.62	15.09	15.57	16.12	16.63	16.87	16.75	16.37	15.83	15.20	14.55	13.93
15	14.61	15.14	15.65	16.17	16.74	17.25	17.47	17.34	16.93	16.37	15.76	15.17	14.63
10	14.73	15.26	15.80	16.34	16.94	17.44	17.67	17.56	17.18	16.65	16.10	15.61	15.16
5	14.50	14.99	15.52	16.10	16.71	17.22	17.47	17.42	17.11	16.66	16.21	15.83	15.49
0	13.94	14.37	14.87	15.46	16.10	16.62	16.90	16.94	16.73	16.38	16.05	15.81	15.59
-5	13.13	13.45	13.91	14.50	15.14	15.65	15.97	16.10	16.00	15.77	15.58	15.50	15.42
-10	12.11	12.31	12.71	13.29	13.89	14.35	14.68	14.90	14.91	14.80	14.74	14.84	14.94
-15	10.75	10.91	11.23	11.69	12.18	12.70	13.00	13.25	13.25	13.32	13.48	13.78	14.09
-20	9.21	9.06	9.29	9.70	10.21	10.25	10.41	10.65	10.84	10.62	10.74	11.93	12.78
-25	7.55	7.50	7.72	7.88	7.86	7.37	7.08	7.24	7.43	7.71	8.47	9.55	10.22
-30	6.36	6.02	5.86	5.79	5.42	5.23	5.10	5.16	5.19	5.39	5.89	6.58	7.99
-35	5.24	4.59	4.45	4.31	4.07	3.72	3.35	3.32	3.37	3.65	4.10	4.90	5.65
-40	4.29	3.74	3.40	3.21	2.83	2.43	2.08	2.00	2.01	2.21	2.65	3.24	4.11
-45	3.46	2.96	2.53	2.30	1.93	1.53	1.28	1.12	1.11	1.25	1.51	2.04	2.72
-50	2.87	2.37	1.95	1.60	1.27	0.94	0.66	0.54	0.53	0.60	0.84	1.15	1.63
-55	2.23	1.79	1.42	1.12	0.87	0.53	0.34	0.23	0.21	0.26	0.38	0.59	0.90
-60	1.78	1.32	1.03	0.75	0.49	0.30	0.15	0.08	0.06	0.08	0.14	0.27	0.48
-65	1.30	0.98	0.72	0.50	0.30	0.15	0.06	0.00	0.00	0.00	0.03	0.11	0.23
-70	0.89	0.64	0.47	0.31	0.18	0.08	0.00	0.00	0.00	0.00	0.00	0.03	0.10
-75	0.59	0.43	0.30	0.19	0.10	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.05
-80	0.37	0.28	0.19	0.13	0.07	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.03

Table A3.4 The $5^{\circ} \times 15^{\circ}$ world grids of trajectory-derived effective vertical cutoff rigidities for epoch 1975.0 (According to Shea and Smart, 1975b)

Geographic					Ge	ographi	c longitu	de				
latitude	195	210	225	240	255	270	285	300	315	330	345	360
80	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02
75	0.14	0.09	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.07	0.10
70	0.36	0.23	0.13	0.06	0.00	0.00	0.00	0.00	0.05	0.11	0.18	0.26
65	0.74	0.53	0.32	0.17	0.09	0.05	0.04	0.08	0.16	0.28	0.42	0.58
60	1.40	1.00	0.65	0.40	0.22	0.16	0.14	0.21	0.38	0.59	0.86	1.14
55	2.22	1.75	1.23	0.78	0.50	0.36	0.36	0.46	0.75	1.13	1.59	1.94
50	3.38	2.81	2.03	1.41	0.95	0.73	0.69	0.69	1.34	1.98	2.65	3.21
45	4.85	4.08	3.16	2.37	1.74	1.32	1.22	1.49	2.21	3.16	4.20	4.77
40	6.46	5.41	4.55	3.61	2.76	2.07	1.93	2.42	3.41	4.82	5.92	6.75
35	8.97	7.65	6.12	5.21	4.25	3.19	2.89	3.58	4.98	6.80	8.70	9.54
30	10.48	9.63	8.78	7.00	5.60	4.44	4.07	4.87	6.98	9.67	10.66	11.30
25	12.43	11.81	10.98	9.74	7.89	6.08	5.44	6.56	9.65	11.47	12.46	13.10
20	13.40	12.91	12.33	11.47	9.69	7.82	6.84	8.65	11.45	12.76	13.54	14.11
15	14.16	13.76	13.30	12.62	11.27	9.49	8.46	10.71	12.52	13.43	14.07	14.61
10	14.75	14.39	14.00	13.44	12.55	11.50	11.07	12.16	13.09	13.76	14.21	14.73
5	15.15	14.82	14.47	14.03	13.41	12.67	12.40	12.78	13.36	13.80	14.11	14.50
0	15.32	15.03	14.71	14.33	13.86	13.32	12.95	13.05	13.38	13.56	13.69	13.94
-5	15.25	15.02	14.74	14.41	14.01	13.53	13.14	13.08	13.19	13.15	13.04	13.13
-10	14.90	14.76	14.15	14.29	13.94	13.51	13.10	12.92	12.82	12.55	12.20	12.11
-15	14.24	14.24	14.15	13.97	13.69	13.30	12.89	12.59	12.31	11.76	11.15	10.75
-20	13.19	13.44	13.51	13.46	13.28	12.94	12.53	12.14	11.65	10.73	9.78	9.21
-25	11.22	12.01	12.63	12.76	12.72	12.46	12.04	11.53	10.74	9.63	8.36	7.55
-30	9.45	9.43	10.64	11.85	12.00	11.88	11.43	10.75	9.83	8.39	7.09	6.36
-35	6.54	7.88	9.11	9.58	11.12	11.16	10.67	9.90	8.72	7.16	6.18	5.24
-40	4.76	5.56	6.65	8.20	9.75	10.18	9.77	8.98	7.61	6.42	5.31	4.29
-45	3.33	4.24	4.93	5.91	7.83	9.00	8.76	7.84	6.91	5.63	4.32	3.46
-50	2.24	2.94	3.76	4.48	5.57	7.02	7.57	6.98	5.68	4.51	3.50	2.87
-55	1.38	1.88	2.64	3.38	4.20	4.96	5.19	5.02	4.45	3.67	2.93	2.23
-60	0.79	1.18	1.62	2.23	3.00	3.77	3.95	3.97	3.52	2.88	2.27	1.78
-65	0.43	0.71	1.06	1.51	1.98	2.53	2.71	2.72	2.50	2.10	1.61	1.30
-70	0.22	0.41	0.64	0.96	1.24	1.58	1.75	1.80	1.67	1.39	1.14	0.89
-75	0.12	0.23	0.36	0.54	0.72	0.91	1.02	1.03	1.05	0.88	0.76	0.59
-80	0.08	0.13	0.21	0.30	0.40	0.48	0.55	0.56	0.54	0.49	0.42	0.37

Table A3.4 (Continued)

Geograph	nic					Geogr	aphic lo	ngitude					
latitude	0	15	30	45	60	75	90	105	120	135	150	165	180
75	-0.02	-0.01	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.04	-0.01	-0.03	-0.03	-0.02
70	-0.03	-0.03	-0.03	-0.02	-0.03	-0.05	-0.04	-0.05	-0.05	-0.04	0.00	-0.04	-0.04
65	-0.02	-0.01	-0.08	-0.04	-0.07	-0.04	-0.03	-0.07	-0.05	-0.02	-0.02	-0.06	-0.08
60	0.00	-0.03	-0.04	-0.08	-0.08	-0.07	-0.08	-0.07	-0.06	-0.01	-0.11	-0.11	-0.09
55	-0.08	-0.04	-0.07	0.00	-0.06	0.00	-0.07	-0.07	-0.02	-0.10	-0.05	-0.09	-0.07
50	0.15	0.02	-0.07	-0.61	-0.01	-0.01	-0.03	-0.21	-0.08	-0.05	-0.03	-0.04	-0.09
45	0.06	-0.06	-0.06	-0.11	-0.03	-0.08	-0.07	-0.05	-0.07	-0.08	-0.09	-0.14	-0.04
40	0.11	-0.10	-0.09	-0.11	-0.04	-0.02	-0.02	-0.10	-0.19	-0.05	-0.06	-0.08	-0.19
35	0.05	0.03	0.15	-0.08	0.05	-0.21	-0.14	-0.13	-0.07	-0.03	-0.04	-0.16	-0.14
30	0.06	-0.05	0.00	0.03	0.03	0.00	-0.07	-0.11	-0.09	-0.09	-0.11	-0.16	-0.23
25	0.11	0.05	0.04	0.07	0.07	0.02	-0.06	-0.09	-0.09	-0.09	-0.11	-0.16	-0.22
20	0.10	0.06	0.10	0.13	0.11	0.04	-0.05	-0.09	-0.08	-0.08	-0.11	-0.17	-0.23
15	0.10	0.09	0.13	0.16	0.13	0.05	-0.05	-0.08	-0.07	-0.07	-0.11	-0.17	-0.23
10	0.07	0.10	0.15	0.15	0.13	0.04	-0.04	-0.07	-0.06	-0.07	-0.11	-0.16	-0.21
5	0.01	0.07	0.11	0.12	0.09	0.02	-0.05	-0.08	-0.08	-0.08	-0.11	-0.15	-0.19
0	-0.09	0.00	0.03	0.03	0.02	-0.01	-0.05	-0.07	-0.09	-0.11	-0.12	-0.14	-0.16
-5	-0.21	-0.10	-0.07	-0.07	-0.06	-0.05	-0.04	-0.04	-0.12	-0.15	-0.15	-0.14	-0.13
-10	-0.34	-0.21	-0.18	-0.17	-0.13	-0.06	-0.03	-0.05	-0.13	-0.19	-0.19	-0.14	-0.11
-15	-0.34	-0.25	-0.30	-0.33	-0.21	-0.04	0.01	-0.01	-0.19	-0.26	-0.20	-0.13	-0.08
-20	-0.34	-0.32	-0.41	-0.30	-0.07	-0.05	0.05	0.05	-0.12	-0.15	-0.20	-0.09	-0.09
-25	-0.52	-0.26	-0.18	-0.26	-0.21	-0.23	-0.03	0.05	-0.17	-0.20	-0.17	-0.11	-0.15
-30	-0.49	-0.20	-0.24	-0.12	-0.26	-0.14	-0.02	0.08	-0.01	-0.15	-0.09	-0.14	0.03
-35	-0.42	-0.24	-0.14	-0.10	-0.17	-0.19	-0.01	0.04	-0.07	-0.07	-0.16	0.01	-0.07
-40	-0.29	-0.18	-0.19	-0.11	-0.12	-0.20	-0.10	-0.02	-0.08	-0.07	-0.05	-0.07	-0.05
-45	-0.28	-0.17	-0.17	-0.06	-0.13	-0.13	-0.07	-0.05	-0.03	-0.02	-0.04	-0.01	-0.03
-50	-0.28	-0.07	-0.12	-0.14	-0.10	-0.10	-0.10	-0.06	-0.02	-0.04	0.01	0.00	-0.04
-55	-0.24	-0.10	-0.11	-0.07	-0.01	-0.06	-0.05	-0.05	-0.02	-0.01	0.00	-0.01	-0.05
-60	-0.12	-0.12	-0.07	-0.05	-0.04	-0.06	-0.04	-0.02	-0.01	-0.01	-0.02	0.00	-0.01
-65	-0.14	-0.06	-0.05	-0.01	-0.02	-0.03	-0.01	-0.03	-0.01	-0.02	-0.01	-0.01	0.00
-70	-0.10	-0.09	-0.04	-0.01	-0.01	0.00	-0.03	-0.01	0.00	0.00	-0.01	-0.01	0.00
-75	-0.05	-0.06	-0.02	-0.02	-0.02	0.00	-0.01	0.00	0.00	0.00	0.00	-0.01	0.00

Table A3.5 The planetary distribution of the differences of CR effective vertical cutoff rigidities in 1955 and 1975 (the rigidity values are given in GV with the 1955 values subtracted from 1975 values) (According to Shea and Smart, 1975b)

Geographic					Ge	eographi	c longitu	ıde				
latitude	195	210	225	240	255	270	285	300	315	330	345	360
75	-0.02	0.00	-0.02	-0.02	0.00	0.00	0.00	0.00	-0.01	-0.01	0.01	-0.02
70	-0.02	-0.03	-0.01	0.00	-0.02	-0.01	-0.01	-0.02	0.00	0.01	-0.01	-0.03
65	-0.06	-0.05	-0.03	-0.03	0.00	0.00	0.00	0.01	0.02	-0.01	-0.01	-0.02
60	-0.08	-0.06	-0.06	-0.03	-0.02	0.00	0.00	0.02	0.04	0.04	0.01	0.00
55	-0.12	-0.05	-0.04	-0.02	0.00	0.00	0.04	0.05	0.09	0.07	0.06	-0.08
50	-0.24	-0.04	-0.05	-0.04	-0.01	0.02	0.06	0.10	0.15	0.17	0.07	0.15
45	-0.07	-0.14	-0.04	-0.05	0.01	0.05	0.08	0.14	0.23	0.19	0.19	0.06
40	-0.14	-0.19	-0.13	-0.14	-0.12	-0.07	0.06	0.32	0.45	0.32	0.27	0.11
35	-0.24	-0.22	-0.24	-0.17	-0.10	-0.04	0.07	0.47	0.48	0.74	0.27	0.05
30	-0.30	-0.27	-0.33	-0.35	-0.23	-0.15	0.14	0.63	1.10	0.76	0.20	0.06
25	-0.28	-0.33	-0.39	-0.37	-0.32	-0.16	0.29	0.76	1.21	0.55	0.29	0.11
20	-0.28	-0.34	-0.37	-0.42	-0.77	-0.27	-0.15	0.98	1.07	0.36	0.22	0.10
15	-0.28	-0.32	-0.36	-0.41	-0.57	-0.30	0.83	1.45	0.41	0.25	0.17	0.10
10	-0.26	-0.29	-0.31	-0.38	-0.42	-0.21	0.27	0.48	0.22	0.14	0.09	0.07
5	-0.22	-0.24	-0.27	-0.31	-0.34	-0.23	0.07	0.07	0.06	0.01	-0.02	0.01
0	-0.19	-0.21	-0.24	-0.28	-0.31	-0.29	-0.20	-0.09	-0.09	-0.13	-0.15	-0.09
-5	-0.15	-0.17	-0.20	-0.25	-0.30	-0.33	-0.30	-0.23	-0.23	-0.28	-0.30	-0.21
-10	-0.12	-0.14	-0.19	-0.24	-0.31	-0.37	-0.38	-0.34	-0.35	-0.42	-0.46	-0.34
-15	-0.10	-0.13	-0.18	-0.24	-0.32	-0.41	-0.44	-0.43	-0.45	-0.57	-0.47	-0.34
-20	-0.08	-0.13	-0.18	-0.24	-0.33	-0.44	-0.49	-0.50	-0.54	-0.71	-0.65	-0.34
-25	0.00	-0.10	-0.17	-0.25	-0.33	-0.45	-0.54	-0.58	-0.71	-0.84	-0.67	-0.52
-30	-0.01	-0.11	0.02	-0.24	-0.33	-0.44	-0.58	-0.69	-0.79	-0.89	-0.64	-0.49
-35	-0.09	-0.05	-0.13	-0.03	-0.28	-0.44	-0.70	-0.73	-0.88	-0.87	-0.55	-0.42
-40	-0.15	-0.03	-0.10	-0.18	0.11	-0.52	-0.64	-0.75	-0.93	-0.73	-0.62	-0.29
-45	-0.09	-0.07	0.01	-0.01	-0.04	-0.30	-0.57	-0.76	-0.76	-0.91	-0.47	-0.28
-50	-0.04	-0.03	-0.04	-0.05	-0.04	-0.17	-0.44	-0.69	-0.90	-0.59	-0.46	-0.28
-55	-0.03	-0.06	-0.01	-0.02	-0.12	-0.16	-0.33	-0.48	-0.51	-0.35	-0.34	-0.24
-60	-0.01	-0.06	-0.12	-0.09	-0.07	-0.12	-0.31	-0.27	-0.40	-0.41	-0.23	-0.12
-65	-0.02	-0.02	-0.06	-0.04	-0.10	-0.12	-0.19	-0.22	-0.25	-0.27	-0.25	-0.14
-70	-0.01	0.00	-0.02	-0.02	-0.07	-0.06	-0.14	-0.17	-0.20	-0.21	-0.17	-0.10
-75	0.00	-0.01	-0.02	-0.02	-0.05	-0.03	-0.05	-0.14	-0.06	-0.12	-0.07	-0.05

Table A3.5 (Continued)

Geographic					Geo	graphic l	ongitude	e (E)				
latitude	0	15	30	45	60	75	90	105	120	135	150	165
80	0.02	0.05	0.06	0.08	0.09	0.09	0.10	0.10	0.11	0.10	0.10	0.08
75	0.10	0.14	0.17	0.20	0.22	0.22	0.25	0.25	0.26	0.26	0.26	0.24
70	0.27	0.34	0.39	0.44	0.48	0.51	0.51	0.55	0.58	0.60	0.61	0.57
65	0.60	0.69	0.80	0.87	0.91	0.94	0.99	1.03	1.12	1.23	1.18	1.11
60	1.16	1.36	1.43	1.59	1.62	1.68	1.70	1.80	1.96	2.05	2.12	2.06
55	2.00	2.29	2.45	2.53	2.67	2.73	2.84	2.93	3.12	3.31	3.31	3.15
50	3.32	3.59	3.83	3.94	4.06	4.20	4.34	4.45	4.69	5.00	4.97	4.69
45	4.99	5.20	5.35	5.44	5.66	5.81	6.08	6.31	6.59	6.96	6.96	6.36
40	6.95	7.44	7.59	7.73	8.07	8.54	8.99	9.23	9.57	9.99	9.82	9.05
35	9.77	9.74	10.01	10.42	10.88	11.27	11.39	11.67	11.95	12.18	11.69	10.67
30	11.49	11.83	12.10	12.51	13.09	13.82	14.19	14.31	14.23	13.97	13.45	12.75
25	13.25	13.68	14.03	14.38	14.86	15.37	15.69	15.70	15.47	15.05	14.46	13.76
20	14.17	14.61	14.99	15.39	15.91	16.43	16.73	16.68	16.36	15.85	15.21	14.54
15	14.63	15.10	15.54	15.99	16.54	17.07	17.35	17.27	16.91	16.37	15.75	15.14
10	14.70	15.19	15.67	16.17	16.75	17.29	17.57	17.50	17.15	16.63	16.06	15.56
5	14.41	14.88	15.38	15.94	16.57	17.11	17.41	17.38	17.07	16.61	16.15	15.77
0	13.80	14.22	14.73	15.34	16.00	16.56	16.87	16.90	16.67	16.31	15.97	15.74
-5	12.94	13.27	13.77	14.41	15.10	15.64	15.97	16.07	15.94	15.68	15.50	15.42
-10	11.86	12.11	12.57	13.23	13.90	14.40	14.71	14.88	14.84	14.69	14.55	14.77
-15	10.45	10.63	11.08	11.75	12.32	12.80	13.06	13.24	13.17	13.18	13.39	13.69
-20	8.87	8.89	9.26	9.74	10.24	10.45	10.55	10.69	10.75	10.66	10.57	11.87
-25	7.28	7.29	7.63	7.93	8.02	7.71	7.28	7.26	7.42	7.64	8.36	9.49
-30	6.11	5.84	5.84	5.80	5.58	5.40	5.19	5.14	5.09	5.38	5.84	6.60
-35	5.05	4.49	4.37	4.35	4.12	3.85	3.47	3.41	3.34	3.55	4.10	4.90
-40	4.03	3.62	3.38	3.26	2.84	2.58	2.21	2.04	2.04	2.22	2.53	3.29
-45	3.33	2.68	2.53	2.38	2.00	1.54	1.25	1.12	1.10	1.21	1.47	2.01
-50	2.76	2.27	1.97	1.64	1.30	0.92	0.71	0.54	0.53	0.60	0.80	1.15
-55	2.17	1.72	1.45	1.12	0.82	0.56	0.35	0.24	0.21	0.25	0.38	0.57
-60	1.69	1.29	1.03	0.76	0.49	0.30	0.15	0.09	0.06	0.08	0.14	0.26
-65	1.29	0.95	0.72	0.48	0.24	0.14	0.06	0.00	0.00	0.00	0.03	0.10
-70	0.84	0.56	0.45	0.30	0.16	0.08	0.00	0.00	0.00	0.00	0.00	0.02
-75	0.59	0.42	0.28	0.18	0.10	0.04	0.00	0.00	0.00	0.00	0.00	0.00
-80	0.34	0.26	0.18	0.12	0.07	0.02	0.00	0.00	0.00	0.00	0.00	0.00

Table A3.6 The $5^{\circ} \times 15^{\circ}$ world grids of trajectory-derived effective vertical cutoff rigidities (in GV) for epoch 1980.0 (According to Shea and Smart, 1983)

Geographic					Geo	graphic l	ongitude	e (E)				
latitude	180	195	210	225	240	255	270	285	300	315	330	345
80	0.07	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
75	0.19	0.14	0.09	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.07
70	0.47	0.34	0.23	0.13	0.06	0.00	0.00	0.00	0.00	0.05	0.11	0.19
65	0.99	0.77	0.49	0.31	0.17	0.09	0.05	0.05	0.09	0.17	0.30	0.43
60	1.75	1.38	0.98	0.65	0.40	0.23	0.16	0.16	0.23	0.39	0.64	0.90
55	2.85	2.28	1.75	1.23	0.81	0.49	0.36	0.36	0.50	0.80	1.21	1.70
50	4.25	3.46	2.81	2.05	1.42	0.97	0.75	0.72	0.94	1.43	2.13	2.85
45	5.60	4.85	4.15	3.16	2.37	1.75	1.35	1.27	1.62	2.47	3.35	4.35
40	7.96	6.47	5.49	4.60	3.63	2.77	2.14	2.05	2.57	3.79	5.08	6.15
35	9.52	8.99	7.67	6.11	5.17	4.21	3.24	2.99	3.83	5.26	7.36	9.11
30	11.59	10.48	9.65	8.78	6.99	5.54	4.38	4.02	5.14	7.54	10.02	10.94
25	13.04	12.38	11.74	10.88	9.63	7.74	6.02	5.51	7.02	9.98	11.78	12.68
20	13.90	13.33	12.84	12.23	11.32	9.35	7.67	6.51	8.49	11.67	12.88	13.63
15	14.59	14.09	13.67	13.19	12.46	11.05	9.27	8.64	11.01	12.60	13.50	14.12
10	15.10	14.68	14.30	13.88	13.35	12.36	11.27	11.06	12.22	13.11	13.78	14.25
5	15.43	15.07	14.73	14.36	13.92	13.22	12.45	12.29	12.73	13.33	13.76	14.04
0	15.53	15.25	14.93	14.60	14.21	13.71	13.14	12.80	12.97	13.32	13.48	13.55
-5	15.35	15.17	14.92	14.62	14.28	13.85	13.36	12.99	12.98	13.09	13.00	12.85
-10	14.87	14.82	14.66	14.43	14.15	13.81	13.37	12.97	12.81	12.69	12.36	11.92
-15	14.01	14.17	14.15	14.03	13.84	13.57	13.19	12.77	12.47	12.15	11.53	10.79
-20	12.72	13.15	13.36	13.42	13.35	13.17	12.85	12.42	11.99	11.47	10.49	9.47
-25	10.10	11.24	11.98	12.56	12.67	12.63	12.38	11.94	11.40	10.52	9.35	8.04
-30	7.98	9.45	9.40	10.75	11.79	11.92	11.78	11.34	10.56	9.57	8.15	6.88
-35	5.65	6.62	8.01	8.73	9.62	11.05	11.09	10.55	9.73	8.50	6.88	5.95
-40	4.15	4.84	5.60	6.76	8.18	9.73	10.08	9.63	8.80	7.35	6.18	5.00
-45	2.69	3.30	4.28	4.99	6.01	7.87	8.89	8.52	7.74	6.80	5.34	4.15
-50	1.64	2.24	2.94	3.79	4.58	5.61	7.05	7.41	6.77	5.47	4.27	3.42
-55	0.95	1.36	1.94	2.64	3.35	4.29	4.90	5.18	4.90	4.25	3.48	2.77
-60	0.51	0.76	1.20	1.77	2.27	2.98	3.75	4.01	3.82	3.39	2.72	2.14
-65	0.22	0.42	0.69	1.05	1.55	1.96	2.46	2.72	2.63	2.40	2.02	1.61
-70	0.10	0.22	0.40	0.60	0.90	1.20	1.51	1.67	1.75	1.59	1.33	1.11
-75	0.04	0.11	0.22	0.34	0.53	0.70	0.87	1.01	1.04	0.98	0.86	0.72
-80	0.02	0.07	0.12	0.20	0.28	0.39	0.45	0.52	0.54	0.53	0.50	0.39

Table A3.6 (Continued)

Geographic					Geog	graphic e	ast long	itude				
latitude	0	15	30	45	60	75	90	105	120	135	150	165
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80	0.02	0.04	0.05	0.07	0.08	0.09	0.09	0.10	0.10	0.09	0.09	0.07
75	0.10	0.13	0.16	0.20	0.21	0.22	0.24	0.00	0.25	0.24	0.25	0.21
70	0.27	0.34	0.39	0.42	0.44	0.45	0.48	0.51	0.56	0.57	0.57	0.53
65	0.57	0.71	0.79	0.83	0.89	0.93	0.94	0.99	1.06	1.15	1.18	1.09
60	1.15	1.34	1.44	1.55	1.54	1.64	1.64	1.72	1.87	2.03	2.04	1.95
55	2.07	2.24	2.40	2.45	2.58	2.58	2.78	2.80	3.06	3.22	3.22	3.04
50	3.27	3.56	3.65	3.82	3.93	4.10	4.19	4.34	4.58	4.90	4.86	4.65
45	4.95	5.13	5.19	5.37	5.49	5.72	5.92	6.06	6.48	6.79	6.78	6.29
40	7.10	7.35	7.41	7.53	7.82	8.29	8.76	9.04	9.48	9.86	9.71	8.92
35	9.72	9.86	9.97	10.23	10.85	11.35	11.28	11.50	11.86	12.09	11.60	10.55
30	11.56	11.78	11.95	12.34	12.85	13.61	14.06	14.22	14.17	13.92	13.40	12.67
25	13.27	13.65	13.96	14.28	14.75	15.26	15.59	15.63	15.44	15.02	14.41	13.68
20	14.19	14.58	14.93	15.30	15.81	16.34	16.65	16.64	16.34	15.82	15.16	14.47
15	14.62	15.07	15.47	15.91	16.46	17.00	17.31	17.26	16.91	16.35	15.70	15.07
10	14.66	15.14	15.60	16.10	16.70	17.26	17.57	17.52	17.16	16.61	16.02	15.49
5	14.33	14.81	15.32	15.89	16.55	17.12	17.44	17.42	17.09	16.60	16.11	15.70
0	13.68	14.13	14.66	15.31	16.01	16.60	16.94	16.96	16.69	16.29	15.93	15.67
-5	12.77	13.15	13.70	14.40	15.14	15.72	16.06	16.14	15.96	15.66	15.45	15.36
-10	11.66	11.97	12.51	13.24	13.96	14.50	14.82	14.94	14.85	14.67	14.61	14.69
-15	10.18	10.52	11.07	11.79	12.44	12.93	13.17	13.29	13.19	13.19	13.35	13.63
-20	8.65	8.78	9.28	9.85	10.35	10.67	10.65	10.75	10.79	10.65	10.65	11.84
-25	7.14	7.31	7.60	8.03	8.18	7.82	7.41	7.34	7.41	7.63	8.36	9.46
-30	5.92	5.73	5.88	5.87	5.75	5.44	5.26	5.20	5.15	5.31	5.86	6.53
-35	4.79	4.43	4.34	4.34	4.20	3.93	3.48	3.37	3.34	3.55	4.14	4.90
-40	3.91	3.55	3.43	3.33	2.92	2.60	2.17	2.00	1.99	2.15	2.58	3.25
-45	3.19	2.83	2.54	2.32	1.97	1.63	1.30	1.10	1.10	1.23	1.46	2.08
-50	2.58	2.22	1.92	1.64	1.26	0.96	0.68	0.54	0.55	0.61	0.79	1.13
-55	2.02	1.70	1.39	1.12	0.80	0.55	0.34	0.24	0.20	0.24	0.38	0.58
-60	1.60	1.27	1.00	0.77	0.50	0.29	0.16	0.09	0.06	0.08	0.15	0.27
-65	1.20	0.91	0.72	0.48	0.29	0.16	0.06	0.00	0.00	0.00	0.03	0.11
-70	0.84	0.63	0.47	0.28	0.16	0.08	0.00	0.00	0.00	0.00	0.00	0.02
-75	0.54	0.39	0.29	0.18	0.10	0.04	0.00	0.00	0.00	0.00	0.00	0.00
-80	0.32	0.24	0.18	0.11	0.07	0.02	0.00	0.00	0.00	0.00	0.00	0.00
-85	0.17	0.14	0.11	0.09	0.06	0.04	0.02	0.01	0.00	0.00	0.00	0.02
-90	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

Table A3.7 The $5^{\circ} \times 15^{\circ}$ world grids of trajectory-derived effective vertical cutoff rigidities (in GV) for the epoch 1990.0 (According to Smart and Shea, 1997a)

Geographic					Geog	graphic e	ast long	itude				
latitude	180	195	210	225	240	255	270	285	300	315	330	345
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80	0.05	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
75	0.18	0.13	0.08	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07
70	0.45	0.35	0.22	0.12	0.06	0.00	0.00	0.00	0.02	0.06	0.12	0.19
65	0.94	0.71	0.53	0.31	0.17	0.09	0.06	0.06	0.10	0.18	0.30	0.45
60	1.71	1.35	0.97	0.66	0.39	0.23	0.18	0.18	0.26	0.44	0.66	0.93
55	2.77	2.25	1.69	1.20	0.79	0.52	0.40	0.40	0.53	0.88	1.28	1.73
50	4.23	3.47	2.74	2.04	1.43	1.00	0.78	0.77	1.04	1.58	2.27	2.81
45	5.50	4.84	4.15	3.24	2.38	1.72	1.36	1.34	1.77	2.60	3.63	4.49
40	7.83	6.42	5.41	4.61	3.63	2.75	2.19	2.14	2.70	4.08	5.26	6.30
35	9.49	8.95	7.65	6.07	5.09	4.13	3.18	3.14	4.02	5.56	7.85	9.26
30	11.60	10.42	9.68	8.65	6.83	5.42	4.35	4.18	5.35	8.36	10.34	11.13
25	12.95	12.28	11.64	10.76	9.45	7.52	5.89	5.67	7.71	10.54	12.02	12.80
20	13.80	13.23	12.72	12.06	11.10	8.96	7.51	6.97	9.19	11.96	13.01	13.70
15	14.49	13.98	13.54	13.03	12.23	10.65	9.07	9.05	11.49	12.74	13.57	14.14
10	15.00	14.56	14.16	13.73	13.13	12.12	11.14	11.26	12.32	13.17	13.77	14.21
5	15.33	14.95	14.58	14.19	13.72	13.01	12.32	12.26	12.74	13.32	13.66	13.95
0	15.42	15.12	14.78	14.43	14.01	13.51	12.96	12.70	12.91	13.22	13.33	13.40
-5	15.25	15.04	14.76	14.45	14.09	13.66	13.17	12.85	12.86	12.93	12.78	12.64
-10	14.77	14.69	14.51	14.27	13.98	13.62	13.17	12.79	12.63	12.46	12.06	11.64
-15	13.92	14.04	14.00	13.88	13.68	13.39	12.99	12.56	12.25	11.86	11.21	10.44
-20	12.63	13.02	13.23	13.28	13.20	13.00	12.64	12.19	11.72	11.06	10.06	9.13
-25	10.03	11.12	11.88	12.45	12.55	12.46	12.16	11.67	11.01	10.14	8.86	7.70
-30	7.96	9.36	9.16	10.74	11.69	11.77	11.58	11.03	10.23	9.11	7.63	6.64
-35	5.60	6.51	7.92	8.33	9.78	10.91	10.85	10.22	9.34	7.94	6.51	5.56
-40	4.12	4.73	5.47	6.69	8.21	9.68	9.80	9.31	8.35	6.89	5.94	4.69
-45	2.69	3.34	4.30	4.89	6.04	7.78	8.72	8.24	7.50	6.45	4.88	3.82
-50	1.59	2.25	2.95	3.79	4.59	5.51	6.84	7.09	6.26	5.03	3.95	3.17
-55	0.95	1.36	1.96	2.62	3.36	4.18	4.80	4.95	4.60	4.00	3.20	2.61
-60	0.45	0.81	1.17	1.69	2.28	2.93	3.65	3.77	3.63	3.19	2.51	1.99
-65	0.23	0.41	0.69	1.05	1.50	1.96	2.39	2.57	2.48	2.26	1.87	1.54
-70	0.10	0.22	0.39	0.61	0.88	1.25	1.50	1.64	1.65	1.51	1.27	1.06
-75	0.04	0.11	0.22	0.34	0.53	0.67	0.82	0.94	0.97	0.92	0.81	0.69
-80	0.02	0.07	0.12	0.19	0.28	0.37	0.44	0.50	0.53	0.50	0.46	0.40
-85	0.04	0.06	0.09	0.12	0.15	0.18	0.21	0.22	0.23	0.22	0.22	0.19
-90	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09

Table A3.7 (Continued)

Geographic					Geog	graphic e	ast long	itude				
latitude	0	15	30	45	60	75	90	105	120	135	150	165
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
85	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.01
80	0.02	0.04	0.05	0.06	0.06	0.07	0.07	0.08	0.08	0.07	0.07	0.06
75	0.08	0.13	0.15	0.17	0.19	0.18	0.21	0.23	0.21	0.22	0.22	0.20
70	0.24	0.32	0.38	0.41	0.43	0.43	0.46	0.48	0.51	0.54	0.52	0.51
65	0.59	0.68	0.74	0.83	0.84	0.87	0.91	0.97	1.01	1.10	1.12	1.07
60	1.10	1.28	1.40	1.45	1.53	1.61	1.61	1.72	1.82	1.94	1.99	1.91
55	2.01	2.25	2.35	2.39	2.49	2.59	2.71	2.79	2.98	3.19	3.18	3.06
50	3.30	3.53	3.69	3.74	3.94	3.98	4.18	4.32	4.53	4.90	4.76	4.53
45	4.91	5.13	5.23	5.29	5.47	5.71	5.88	6.06	6.41	6.70	6.70	6.28
40	7.13	7.35	7.36	7.44	7.78	8.23	8.65	8.92	9.36	9.77	9.61	8.80
35	9.76	9.74	9.95	10.27	10.74	11.28	11.22	11.41	11.74	11.99	11.50	10.50
30	11.61	11.76	11.93	12.33	12.82	13.53	14.00	14.16	14.12	13.87	13.36	12.63
25	13.29	13.64	13.94	14.26	14.72	15.22	15.54	15.59	15.40	14.99	14.37	13.64
20	14.19	14.58	14.91	15.28	15.78	16.31	16.62	16.61	16.32	15.80	15.13	14.43
15	14.62	15.06	15.45	15.89	16.44	16.99	17.29	17.25	16.90	16.33	15.67	15.03
10	14.64	15.12	15.58	16.08	16.70	17.26	17.57	17.52	17.16	16.60	16.00	15.45
5	14.30	14.78	15.29	15.88	16.55	17.13	17.46	17.43	17.10	16.59	16.08	15.66
0	13.62	14.09	14.64	15.30	16.02	16.62	16.96	16.98	16.70	16.29	15.91	15.63
-5	12.70	13.10	13.67	14.39	15.15	15.75	16.10	16.17	15.97	15.66	15.44	15.32
-10	11.56	11.91	12.48	13.23	13.98	14.53	14.86	14.98	14.87	14.67	14.60	14.67
-15	10.13	10.47	11.03	11.78	12.43	12.96	13.21	13.33	13.25	13.23	13.33	13.60
-20	8.52	8.75	9.20	9.83	10.33	10.65	10.73	10.80	10.84	10.54	10.66	11.84
-25	7.07	7.23	7.59	7.99	8.12	7.82	7.42	7.38	7.40	7.65	8.40	9.48
-30	5.78	5.72	5.83	5.87	5.71	5.37	5.23	5.16	5.09	5.37	5.82	6.54
-35	4.72	4.33	4.33	4.34	4.18	3.94	3.49	3.36	3.37	3.57	4.11	4.90
-40	3.85	3.52	3.47	3.27	2.89	2.57	2.18	2.06	2.03	2.22	2.58	3.18
-45	3.16	2.78	2.54	2.29	1.92	1.56	1.28	1.10	1.10	1.20	1.47	2.07
-50	2.55	2.16	1.90	1.61	1.31	0.93	0.68	0.53	0.51	0.60	0.75	1.09
-55	2.00	1.68	1.42	1.10	0.81	0.53	0.33	0.23	0.22	0.24	0.36	0.55
-60	1.51	1.21	0.96	0.74	0.50	0.28	0.13	0.07	0.05	0.07	0.12	0.25
-65	1.19	0.90	0.66	0.47	0.27	0.14	0.05	0.02	0.01	0.01	0.03	0.09
-70	0.79	0.61	0.43	0.29	0.15	0.06	0.02	0.00	0.00	0.00	0.01	0.03
-75	0.53	0.38	0.25	0.16	0.08	0.04	0.01	0.00	0.00	0.00	0.00	0.01
-80	0.30	0.24	0.15	0.10	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.01
-85	0.16	0.13	0.10	0.07	0.05	0.04	0.03	0.02	0.02	0.02	0.02	0.03
-90	0.07	0.06	0.07	0.07	0.07	0.06	0.07	0.06	0.07	0.07	0.06	0.07

Table A3.8 The $5^{\circ} \times 15^{\circ}$ world grids of trajectory-derived effective vertical cutoff rigidities (in GV) for the epoch 1995.0 (According to Smart and Shea, 2007a)

Geographic		Geographic east longitude												
latitude	180	195	210	225	240	255	270	285	300	315	330	345		
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
85	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
80	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01		
75	0.17	0.11	0.06	0.03	0.01	0.00	0.00	0.00	0.00	0.01	0.03	0.06		
70	0.42	0.33	0.19	0.10	0.05	0.02	0.01	0.01	0.03	0.05	0.10	0.16		
65	0.91	0.73	0.49	0.30	0.16	0.08	0.05	0.06	0.09	0.18	0.30	0.47		
60	1.69	1.32	0.93	0.64	0.38	0.22	0.17	0.17	0.25	0.44	0.68	0.94		
55	2.74	2.20	1.68	1.21	0.80	0.50	0.38	0.42	0.58	0.91	1.32	1.79		
50	4.18	3.43	2.75	2.07	1.44	1.01	0.78	0.80	1.08	1.62	2.32	2.93		
45	5.44	4.83	4.09	3.13	2.38	1.72	1.38	1.38	1.89	2.65	3.79	4.51		
40	7.73	6.43	5.43	4.64	3.56	2.74	2.20	2.18	2.85	4.14	5.37	6.38		
35	9.43	8.91	7.67	6.03	5.06	4.05	3.21	3.21	4.15	5.68	8.12	9.37		
30	11.59	10.42	9.66	8.66	6.78	5.36	4.33	4.28	5.58	8.57	10.55	11.18		
25	12.91	12.26	11.59	10.71	9.37	7.43	5.93	5.83	7.98	10.73	12.09	12.85		
20	13.76	13.19	12.67	12.00	10.98	8.87	7.41	7.05	9.56	12.06	13.06	13.72		
15	14.44	13.93	13.48	12.96	12.10	10.54	8.99	9.25	11.60	12.79	13.59	14.15		
10	14.95	14.50	14.10	13.65	12.99	12.03	11.10	11.33	12.36	13.18	13.77	14.20		
5	15.27	14.89	14.51	14.11	13.61	12.91	12.26	12.26	12.74	13.30	13.64	13.91		
0	15.37	15.05	14.71	14.34	13.92	13.40	12.87	12.65	12.88	13.17	13.26	13.34		
-5	15.19	14.97	14.69	14.37	14.00	13.57	13.08	12.78	12.80	12.85	12.69	12.55		
-10	14.72	14.62	14.43	14.19	13.89	13.52	13.08	12.71	12.55	12.36	11.92	11.52		
-15	13.87	13.97	13.93	13.81	13.60	13.30	12.89	12.46	12.14	11.73	11.05	10.26		
-20	12.57	12.96	13.16	13.21	13.13	12.91	12.54	12.07	11.59	10.88	9.87	8.93		
-25	9.99	11.02	11.84	12.39	12.49	12.38	12.06	11.55	10.88	9.93	8.68	7.58		
-30	7.90	9.30	9.05	10.75	11.63	11.70	11.46	10.87	9.98	8.90	7.37	6.54		
-35	5.55	6.50	7.87	8.25	9.87	10.85	10.73	10.07	9.11	7.70	6.38	5.45		
-40	4.11	4.66	5.52	6.69	8.15	9.69	9.67	9.14	8.09	6.60	5.73	4.52		
-45	2.62	3.33	4.22	4.89	6.06	7.74	8.64	8.10	7.34	6.23	4.69	3.77		
-50	1.66	2.21	2.91	3.75	4.58	5.47	6.78	6.90	6.08	4.80	3.90	3.11		
-55	0.90	1.36	1.91	2.62	3.35	4.18	4.76	4.81	4.50	3.88	3.16	2.45		
-60	0.46	0.78	1.19	1.73	2.28	2.97	3.58	3.74	3.49	3.07	2.43	1.97		
-65	0.20	0.42	0.65	1.04	1.50	1.94	2.41	2.53	2.39	2.20	1.87	1.47		
-70	0.08	0.21	0.38	0.60	0.91	1.21	1.48	1.61	1.63	1.47	1.24	1.03		
-75	0.04	0.10	0.20	0.34	0.51	0.65	0.81	0.93	0.95	0.87	0.80	0.66		
-80	0.03	0.06	0.11	0.18	0.25	0.34	0.42	0.47	0.48	0.46	0.46	0.36		
-85	0.04	0.05	0.08	0.10	0.12	0.17	0.21	0.19	0.23	0.22	0.19	0.19		
-90	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.06		

Table A3.8 (Continued)

Geographic		Geographic east longitude												
latitude	0	30	60	90	120	150	180	210	240	370	300	330		
90	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
85	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		
80	0.00	0.02	0.05	0.04	0.05	0.03	0.02	0.00	0.00	0.00	0.00	0.00		
75	0.05	0.13	0.19	0.21	0.22	0.21	0.13	0.03	0.00	0.00	0.00	0.00		
70	0.25	0.35	0.42	0.44	0.51	0.52	0.41	0.21	0.03	0.00	0.00	0.12		
65	0.60	0.74	0.81	0.91	0.99	1.09	0.89	0.49	0.16	0.04	0.10	0.32		
60	1.16	1.43	1.51	1.60	1.77	2.01	1.62	1.00	0.39	0.19	0.30	0.72		
55	2.05	2.33	2.44	2.65	2.88	3.11	2.80	1.71	0.81	0.42	0.62	1.36		
50	3.31	3.65	3.83	4.16	4.48	4.72	4.15	2.79	1.43	0.82	1.16	2.41		
45	4.95	5.22	5.48	5.80	6.30	6.58	5.49	4.09	2.37	1.45	1.92	3.90		
40	7.06	7.24	7.71	8.52	9.24	9.43	7.74	5.46	3.62	2.19	2.96	5.52		
35	9.75	9.83	10.82	11.15	11.63	11.35	9.42	7.70	5.08	3.31	4.33	8.42		
30	11.58	11.87	12.82	13.97	14.04	13.29	11.61	9.77	6.74	4.29	5.78	10.66		
25	13.30	13.91	14.72	15.51	15.34	14.31	12.89	11.60	9.29	5.86	8.24	12.18		
20	14.21	14.89	15.80	16.61	16.27	15.08	13.73	12.63	10.86	7.40	10.01	13.12		
15	14.63	15.45	16.47	17.30	16.86	15.63	14.40	13.43	11.99	8.96	11.70	13.62		
10	14.65	15.58	16.74	17.60	17.14	15.96	14.90	14.04	12.91	11.05	12.40	13.77		
5	14.29	15.30	16.61	17.51	17.09	16.06	15.21	14.44	13.53	12.20	12.75	13.62		
0	13.60	14.65	16.10	17.03	16.72	15.90	15.30	14.63	13.83	12.78	12.85	13.20		
-5	12.66	13.70	15.24	16.18	16.02	15.43	15.12	14.60	13.91	12.98	12.74	12.58		
-10	11.50	12.51	14.07	14.94	14.94	14.61	14.63	14.34	13.80	12.97	12.46	11.77		
-15	10.12	11.09	12.49	13.28	13.38	13.36	13.77	13.83	13.51	12.78	12.02	10.86		
-20	8.45	9.32	10.34	10.80	10.73	10.72	12.47	13.06	13.04	12.42	11.45	9.61		
-25	7.03	7.71	8.21	7.47	7.61	8.50	9.87	11.72	12.39	11.94	10.68	8.45		
-30	5.79	5.92	5.61	5.23	5.29	5.81	7.81	8.85	11.54	11.34	9.87	7.18		
-35	4.59	4.33	4.14	3.48	3.37	4.17	5.51	7.81	9.81	10.57	8.91	6.39		
-40	3.78	3.45	2.91	2.14	2.07	2.63	4.06	5.45	8.11	9.51	7.86	5.58		
-45	3.11	2.50	1.94	1.27	1.09	1.50	2.64	4.15	6.01	8.49	7.14	4.51		
-50	2.47	1.91	1.32	0.69	0.52	0.80	1.61	2.91	4.54	6.59	5.85	3.70		
-55	1.93	1.40	0.78	0.36	0.20	0.35	0.93	1.94	3.29	4.61	4.38	2.97		
-60	1.52	1.02	0.49	0.10	0.03	0.14	0.47	1.18	2.26	3.57	3.42	2.37		
-65	1.13	0.67	0.28	0.03	0.00	0.02	0.23	0.72	1.51	2.33	2.38	1.76		
-70	0.80	0.45	0.14	0.00	0.00	0.00	0.06	0.37	0.89	1.43	1.57	1.25		
-75	0.54	0.27	0.05	0.00	0.00	0.00	0.02	0.22	0.50	0.82	0.94	0.76		
-80	0.30	0.14	0.03	0.00	0.00	0.00	0.00	0.07	0.28	0.43	0.48	0.43		
-85	0.17	0.07	0.03	0.00	0.00	0.00	0.00	0.06	0.13	0.20	0.20	0.18		
-90	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04		

Table A3.9 The $5^{\circ} \times 30^{\circ}$ world grids of trajectory-derived effective vertical cutoff rigidities (in GV) for the epoch 2000.0 (According to Smart and Shea, 2007b)

Geographic		Geographic longitude												
latitude	0	30	60	90	120	150	180	210	240	270	300	330	360	
80	0.00	0.05	0.07	0.09	0.09	0.08	0.05	0.00	0.00	0.00	0.00	0.00	0.00	
75	0.09	0.15	0.19	0.22	0.24	0.22	0.16	0.07	0.00	0.00	0.00	0.02	0.09	
70	0.23	0.34	0.41	0.44	0.50	0.50	0.39	0.19	0.05	0.00	0.00	0.10	0.23	
65	0.51	0.72	0.76	0.88	0.96	1.01	0.79	0.43	0.16	0.05	0.09	0.25	0.51	
60	1.02	1.26	1.39	1.48	1.74	1.79	1.48	0.85	0.32	0.16	0.23	0.57	1.02	
55	1.78	2.08	2.28	2.45	2.71	2.82	2.38	1.47	0.74	0.35	0.49	1.09	1.78	
50	2.78	3.22	3.48	3.73	4.05	4.22	3.60	2.37	1.24	0.67	0.94	1.88	2.78	
45	4.24	4.61	4.85	5.24	5.67	5.88	4.75	3.57	2.01	1.22	1.52	3.07	4.24	
40	6.05	6.42	6.92	7.66	8.08	8.37	6.72	4.75	3.08	1.92	2.39	4.43	6.05	
35	8.17	8.45	9.31	9.68	10.19	9.81	8.13	6.64	4.46	2.81	3.52	6.46	8.17	
30	9.74	10.25	11.06	11.82	12.34	11.58	9.98	8.31	5.92	3.79	4.56	8.72	9.74	
25	11.17	11.84	12.64	13.52	13.45	12.66	11.44	10.00	8.15	5.23	6.49	10.06	11.17	
20	12.11	12.91	13.69	14.41	14.22	13.32	12.21	11.18	9.54	6.57	7.71	11.07	12.11	
15	12.63	13.37	14.24	14.96	14.71	13.79	12.79	11.92	10.61	7.78	9.63	11.73	12.63	
10	12.70	13.49	14.45	15.19	14.92	14.05	13.21	12.47	11.42	9.62	10.72	11.96	12.70	
5	12.48	13.29	14.33	15.09	14.86	14.10	13.46	12.82	11.98	10.65	11.17	11.94	12.48	
0	11.99	12.80	13.91	14.67	14.51	13.92	13.50	12.98	12.31	11.30	11.34	11.70	11.99	
-5	11.28	12.06	13.20	13.94	13.86	13.48	13.32	12.96	12.40	11.59	11.33	11.28	11.28	
-10	10.38	11.11	12.25	12.90	12.89	12.72	12.87	12.73	12.31	11.63	11.16	10.68	10.38	
-15	9.25	9.87	10.86	11.41	11.01	11.29	12.12	12.28	12.06	11.48	10.83	9.98	9.25	
-20	7.89	8.31	8.98	9.26	9.12	9.14	10.60	11.61	11.65	11.18	10.38	9.03	7.89	
-25	6.53	6.87	7.17	6.58	6.42	7.22	8.61	9.96	11.07	10.78	9.75	7.98	6.53	
-30	5.45	5.37	5.07	4.60	4.48	5.08	6.80	7.90	10.27	10.18	9.03	6.83	5.45	
-35	4.48	3.97	3.70	3.03	2.94	3.58	4.91	6.94	8.32	9.45	8.17	5.87	4.48	
-40	3.60	3.09	2.58	1.93	1.81	2.28	3.61	4.84	7.08	8.62	7.26	5.24	3.60	
-45	2.89	2.32	1.75	1.15	0.97	1.31	2.36	3.74	5.28	7.52	6.59	4.41	2.89	
-50	2.34	1.74	1.11	0.63	0.50	0.71	1.44	2.56	3.95	5.68	5.45	3.55	2.34	
-55	1.84	1.22	0.67	0.30	0.20	0.34	0.80	1.68	2.91	4.10	4.01	2.85	1.84	
-60	1.40	0.83	0.39	0.14	0.06	0.12	0.42	1.02	1.97	3.05	3.05	2.22	1.40	
-65	0.98	0.60	0.23	0.05	0.00	0.03	0.19	0.63	1.28	2.00	2.12	1.58	0.98	
-70	0.70	0.38	0.13	0.00	0.00	0.00	0.09	0.35	0.77	1.27	1.36	1.05	0.70	
-75	0.44	0.22	0.07	0.00	0.00	0.00	0.04	0.18	0.44	0.72	0.80	0.64	0.44	
-80	0.26	0.14	0.05	0.00	0.00	0.00	0.02	0.10	0.24	0.38	0.42	0.37	0.26	
-85	0.14	0.09	0.04	0.01	0.00	0.00	0.03	0.07	0.13	0.17	0.19	0.17	0.14	
-90	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	

Table A3.10 The $5^{\circ} \times 30^{\circ}$ world grid of trajectory-derived vertical effective cutoff rigidities at altitude 450 km for the epoch 1990.0 (According to Smart and Shea, 1997b)

Table A3.11 World grid $5^{\circ} \times 30^{\circ}$ of trajectory-derived effective cutoff rigidities (in GV) for the west direction at 90° zenith angle at altitude 450 km for the epoch 1990.0 (According to Smart and Shea, 1997b)

Geographic	aphic Geographic east longitude												
latitude	0	30	60	90	120	150	180	210	240	270	300	330	360
80	0.00	0.05	0.07	0.08	0.09	0.08	0.05	0.00	0.00	0.00	0.00	0.00	0.00
75	0.09	0.14	0.19	0.22	0.23	0.22	0.16	0.07	0.00	0.00	0.00	0.02	0.09
70	0.23	0.32	0.40	0.44	0.48	0.50	0.37	0.19	0.05	0.00	0.00	0.10	0.23
65	0.49	0.65	0.77	0.83	0.89	0.94	0.80	0.40	0.16	0.05	0.09	0.24	0.49
60	0.92	1.09	1.25	1.36	1.50	1.61	1.28	0.78	0.33	0.15	0.22	0.55	0.92
55	1.51	1.81	1.97	2.08	2.33	2.48	2.08	1.33	0.67	0.34	0.45	1.01	1.51
50	2.28	2.62	2.80	3.09	3.30	3.75	2.87	2.07	1.16	0.65	0.80	1.73	2.28
45	3.43	3.63	3.81	4.08	4.49	4.50	3.81	2.95	1.79	1.12	1.40	2.50	3.43
40	4.54	4.73	5.07	5.35	5.93	5.75	4.80	3.86	2.62	1.78	2.06	3.82	4.54
35	5.49	5.80	6.10	6.58	6.89	6.87	5.69	4.83	3.60	2.53	2.86	4.94	5.49
30	6.61	7.47	8.13	8.22	9.27	7.85	7.44	5.68	4.73	3.31	3.73	5.73	6.61
25	7.42	7.95	8.93	9.41	10.12	9.40	7.72	6.86	5.45	4.32	4.61	6.39	7.42
20	8.37	8.89	9.53	10.21	10.40	9.69	8.80	8.09	7.40	4.97	5.74	7.56	8.37
15	8.52	9.01	9.68	10.33	10.40	9.79	9.05	8.68	7.75	6.26	6.20	8.62	8.52
10	8.47	8.91	9.53	10.23	10.32	9.84	9.08	6.82	8.25	6.59	6.82	8.69	8.47
5	8.22	8.71	9.37	10.14	10.34	9.98	9.42	8.90	8.42	7.85	8.54	8.43	8.22
0	8.00	8.59	9.16	10.01	10.27	10.09	9.68	9.13	8.55	8.05	8.53	8.11	8.00
-5	7.72	8.29	8.86	9.78	10.12	10.14	9.86	9.28	8.80	8.11	8.25	7.71	7.72
-10	7.26	7.63	8.23	9.10	8.86	8.81	9.81	9.45	9.04	8.18	7.88	7.32	7.26
-15	6.34	6.41	6.78	8.12	7.85	8.25	9.24	9.37	9.28	8.29	7.60	6.92	6.34
-20	5.31	5.93	6.04	5.89	6.13	6.43	7.10	8.24	9.32	8.44	7.29	6.39	5.31
-25	4.99	4.54	4.71	4.95	5.34	5.19	6.24	6.87	7.74	8.52	7.05	5.74	4.99
-30	4.08	3.81	3.91	3.65	3.64	4.05	5.12	5.92	7.50	8.38	6.65	5.15	4.08
-35	3.49	3.10	2.92	2.61	2.47	3.13	4.17	5.55	6.15	8.37	6.12	5.07	3.49
-40	3.09	2.45	2.18	1.75	1.59	2.01	2.91	4.05	4.99	5.87	5.96	4.04	3.09
-45	2.47	1.90	1.58	1.04	0.89	1.21	2.03	2.99	4.25	5.41	4.71	3.51	2.47
-50	2.07	1.46	1.00	0.59	0.45	0.67	1.30	2.26	3.35	4.23	4.17	3.02	2.07
-55	1.63	1.08	0.68	0.29	0.19	0.31	0.77	1.54	2.46	3.69	3.25	2.44	1.63
-60	1.24	0.77	0.42	0.14	0.06	0.13	0.40	0.98	1.86	2.52	2.54	1.92	1.24
-65	0.96	0.55	0.24	0.05	0.00	0.03	0.20	0.59	1.24	1.76	1.82	1.48	0.96
-70	0.65	0.36	0.13	0.00	0.00	0.00	0.09	0.32	0.75	1.14	1.22	0.99	0.65
-75	0.44	0.23	0.07	0.00	0.00	0.00	0.04	0.19	0.42	0.68	0.76	0.63	0.44
-80	0.26	0.13	0.05	0.00	0.00	0.00	0.02	0.10	0.23	0.35	0.42	0.36	0.26
-85	0.14	0.09	0.04	0.01	0.00	0.00	0.03	0.07	0.12	0.17	0.18	0.18	0.14
-90	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

Table A3.12 Values $R_{cik}(h_o)$ depending on type and level of observations, and of type of CR primary variation (According to Dorman and Gushchina, 1967)

No.	Type of observation		Quiet b =	period = 0		Solar CR events $b = -2$			
		Ι	II	III	IV	Ι	Π	III	IV
1	On low satellites and in the stratosphere; $a = -2.5$	7.901	4.700	3.680	2.014	7.845	4.686	3.651	2.006
2	Neutron component for $h_0 = 312 \text{ g/cm}^2$ (10 km); a = -1.445; -0.676; -0.5; -0.206; 0.53	7.935	4.713	3.714	2.022	7.8775	4.70	3.685	2.017
3	Neutron component for $h_o = 680 \text{ g/cm}^2$ (mountain level); $a = -1.145$; -0.382 ; 0; 0; 0.47	7.945	4.716	3.717	2.022	7.915	4.701	3.687	2.016
4	Neutron component at sea level for $h_0 = 1,000 \text{ g/cm}^2$; a = -0.85; 0.353; 0.323; 0.471; 0.884	7.952	4.721	3.723	2.024	7.896	4.707	3.694	2.018
5	Hard component for $h_0 = 312 \text{ g/cm}^2$ (10 km); a = -0.825; 0.265; 0.265; 0.412; 0.912	7.953	4.72	3.722	2.024	7.895	4.706	3.693	2.0185
6	Hard component at sea level for $h_0 = 1,000 \text{ g/cm}^2$; $a = 0.97$; 1.97; 2.12; 2.65	7.998	4.735	3.755	-	7.948	4.719	3.726	-
7	Hard component at sea level underground at depth 3 m.w.e.; a = 2.15; 2.64; 3.17; 5.37	8.028	4.739	3.795	-	7.978	4.724	3.766	-
8	Hard component at sea level underground at depth 7 m.w.e.; a = 2.49; 5.61	8.038	4.757	-	_	7.988	4.746	-	-

No.				Solar CF	events			
		<i>b</i> =	= -4			b =	-6	
	Ι	Π	III	IV	Ι	II	III	IV
1	7.79	4.67	3.622	1.9995	7.735	4.654	3.593	1.992
2	7.818	4.684	3.655	2.010	7.762	4.67	2.627	2.003
3	7.825	4.687	3.658	2.010	7.772	4.672	3.63	2.003
4	7.835	5.692	3.666	2.011	7.780	5.617	3.637	2.004
5	7.84	4.691	3.664	2.012	7.781	4.676	3.635	2.005
6	7.888	4.704	3.697	-	7.825	4,689	3.668	_
7	7.925	4.709	3.736	-	7.865	4.695	3.707	_
8	7.935	4.731	-	-	7.875	4.716	-	-

No.		CR modulation effects in the heliosphere													
		b =	-0.5			b =	-1.0			b =	-1.5				
	Ι	II	III	IV	Ι	Π	III	IV	Ι	II	III	IV			
1	7.89	4.68	3.67	2.01	7.88	4.69	3.67	2.01	7.86	4.69	3.66	2.01			
2	7.92	4.71	3.71	2.02	7.90	4.71	3.70	2.02	7.89	4.70	3.69	2.02			
3	7.93	4.71	3.71	2.02	7.91	4.71	3.70	2.02	7.90	4.70	3.69	2.02			
4	7.94	4.72	3.72	2.02	7.92	4.71	3.71	2.02	7.91	4.71	3.70	2.02			
5	7.94	4.72	3.72	2.02	7.93	4.71	3.71	2.02	7.91	4.71	3.71	2.02			
6	7.99	4.73	3.75	_	7.98	4.73	3.74	_	7.96	4.72	3.73	_			
7	8.01	4.74	3.79	-	8.00	4.73	3.78	-	7.99	4.73	3.77	_			
8	8.02	4.76	-	-	8.01	4.75	-	-	8.00	4.75	-	-			

 Table A3.12 (Continued)



Fig. A3.1 World map of the vertical geomagnetic cutoff rigidities for an altitude of 112.3 km (According to Wentz et al., 2001a)



Fig. A3.2 The directional dependence of the geomagnetic cutoff rigidity for Fort Sumner, New Mexico $(34.3^{\circ}N, 104.1^{\circ}W)$. The counting of the azimuth angle φ follows the convention used by the Super-Kamiokande detector, $\varphi = 0^{\circ}$ means looking to the south, $\varphi = 90^{\circ}$ to the east, etc. (According to Wentz et al., 2001a)



Fig. A3.3 The width of the penumbra region, i.e. the difference between the open trajectory of lowest and the closed trajectory of highest momentum for Fort Sumner (According to Wentz et al., 2001a)



Fig. A3.4 The directional dependence of the geomagnetic cutoff for Kamioka $(36.4 \degree N, 137.3 \degree E)$ (According to Wentz et al., 2001a)



Fig. A3.5 The width of penumbra region for Kamioka site. Large values, i.e., bigger than 2 GV usually indicate gaps in the cutoff (According to Wentz et al., 2001a)



Fig. A3.6 Comparison of the AMS results on primary protons for different intervals of the geomagnetic latitude with the results of the simulation of the geomagnetic cutoff (According to Wentz et al., 2001a)



Fig. A3.7 Comparison of the AMS results on primary helium nuclei with the results of the simulation of the geomagnetic cutoff (According to Wentz et al., 2001a)

Appendix to Chapter 4

Date	Geogr	raphical dinates	(count	s/2 h)/8	$\begin{array}{c} ln(I_{NPW}) \\ (\%) \end{array}$	$\begin{array}{c} I_{MP} \\ (0.01\%) \end{array}$
	λ	φ	I _{NP}	I _{NPW}		
25 Nov. 1956	1.3°N	103.9°E	1,070	1,049	4.8	88
26 Nov. 1956	1.3°N	103.9°E	1,045	1,027	2.7	128
27 Nov. 1956	1.9°N	102.4°E	1,063	1,048	4.7	87
28 Nov. 1956	4.3°N	98.9°E	1,063	1,050	4.9	77
29 Nov. 1956	5.4°N	94.8°E	1,061	1,048	4.7	56
30 Nov. 1956	3.1°N	90.7°E	1,068	1,055	5.4	_
1 Dec. 1956	0.3°N	87.1°E	1,078	1,083	8.0	109
2 Dec. 1956	2.7 ° S	83.5°E	1,105	1,112	10.6	172
3 Dec. 1956	5.6°S	80.0°E	1,121	1,125	11.8	234
4 Dec. 1956	8.6°S	76.7°E	1,171	1,178	16.4	319
5 Dec. 1956	10.7 ° S	72.9°E	1,197	1,212	19.2	390
6 Dec. 1956	12.7°S	69.3°E	1,245	1,258	23.0	462
7 Dec. 1956	15.3°S	65.9°E	1,300	1,329	28.4	636
8 Dec. 1956	18.0° S	62.3°E	1.374	1.383	32.4	798
9 Dec. 1956	20.7 ° S	58.5°E	1,388	1,470	38.6	949
10 Dec. 1956	23.3°S	54.5°E	1.518	1.539	43.1	999
11 Dec. 1956	25.5°S	50.7°E	1.627	1.653	50.8	1.172
12 Dec. 1956	28.1 ° S	47.0°E	1.724	1.749	55.9	1.316
13 Dec. 1956	30.1°S	43.3°E	1.821	1.844	61.2	1.394
14 Dec. 1956	31.6°S	40.0°E	1.954	1.980	68.4	1,441
15 Dec. 1956	33.3°S	35.7°E	1.883	1.899	64.2	1,453
16 Dec. 1956	34.7°S	30.6° E	1.879	1.911	64.8	1,468
17 Dec. 1956	35.1°S	25.7°E	1.931	1,969	67.8	1,479
18 Dec. 1956	35.1°S	20.4°E	1,865	1,913	64.9	1,463
19 Dec. 1956	34.1°S	18.3°E	1.835	1.899	64.1	_
20 Dec. 1956	33.9°S	18.5°E	_	_	_	_
21 Dec. 1956	33.9°S	18.5°E	1,816	1,932	65.9	
22 Dec. 1956	33.9°S	18.5°E	1,789	1,896	64.0	
23 Dec. 1956	33.9°S	18.5°E	1,770	1,883	62.3	
24 Dec. 1956	33.9°S	18.5°E	1,842	1,930	65.8	
25 Dec. 1956	33.9°S	18.5°E	1,779	1,902	64.3	
26 Dec. 1956	33.9°S	18.5°E	1,748	1,893	63.8	
27 Dec. 1956	33.9°S	18.5°E	1,763	1,894	63.9	
28 Dec. 1956	33.9°S	18.5°E	1,737	1,871	62.7	
29 Dec. 1956	34.4°S	18.7°E	1,772	1,869	62.5	
30 Dec. 1956	37.8°S	20.1°E	_	_	_	1,207
31 Dec. 1956	41.7°S	22.2°E	1,900	2,009	69.8	1,262
1 Jan. 1957	45.0°S	26.1°E	1,883	1,991	68.9	1,435
2 Jan. 1957	47.9°S	30.5°E	1,829	1,967	67.7	1,562
3 Jan. 1957	50.7° S	33.1°E	1,851	2,008	69.7	1,566
4 Jan. 1957	53.7°S	35.5°E	1,779	1,907	64.6	1,933
5 Jan. 1957	57.4°S	40.1°E	_	_	_	1,890
6 Jan. 1957	61.0°S	45.4°E	1,868	1,960	67.3	1,921

Table A4.1 Daily data of CR measurements during the 1956/57 expedition (According toFukushima et al., 1963)

Date	Geographical coordinates		(counts	s/2 h)/8	$\begin{array}{c} ln(I_{NPW}) \\ (\%) \end{array}$	$\stackrel{I_{MP}}{(0.01\%)}$
	λ	φ	I _{NP}	I _{NPW}		
7 Jan. 1957	64.2°S	51.2°E	1,923	2,009	69.8	1,896
8 Jan. 1957	65.4°S	49.7°E	1,905	1,985	68.6	_
9 Jan. 1957	65.9° S	45.1°E	1,912	2,010	69.8	_
10 Jan. 1957	66.4° S	41.9°E	1,949	2,054	72.0	_
11 Jan. 1957	66.9° S	39.2°E	1,988	2,088	73.7	_
12 Jan. 1957	67.9°S	35.3°E	1,999	2,097	74.1	_
13 Jan. 1957	67.9°S	35.0°E	2,006	2,071	72.9	_
14 Jan. 1957	67.9°S	34.8°E	2,013	2,107	74.5	_
15 Jan. 1957	67.1°S	38.5°E	2,025	2,135	75.9	_
16 Jan. 1957	67.1°S	40.2°E	1,999	2,074	73.0	_
17 Jan. 1957	67.5°S	39.9°E	2,012	2,060	72.3	_
18 Jan. 1957	68.0° S	40.3°E	1,986	2,021	70.4	_
19 Jan. 1957	68.4°S	38.8°E	1,985	2,026	70.7	_
20 Jan. 1957	68.9°S	38.8°E	1,992	2,022	70.4	_
21 Jan. 1957	69.0° S	39.0°E	1,967	2,042	71.4	_
22 Jan. 1957	69.0° S	39.0°E	1,779	2,116	75.0	_
23 Jan. 1957	69.0° S	39.1°E	1,774	2,043	71.5	_
24 Jan. 1957	69.0° S	39.1°E	1,849	2,068	72.7	_
25 Jan. 1957	69.0° S	39.1°E	1,862	2,037	71.2	_
26 Jan. 1957	69.0° S	39.1°E	1,907	2,085	73.5	_
27 Jan. 1957	69.0° S	39.1°E	1,902	2,081	73.3	_
28 Jan. 1957	69.0° S	39.1°E	1,915	2,045	71.6	_
29 Jan. 1957	69.0° S	39.1°E	1,895	2,007	69.7	_
30 Jan. 1957	69.0° S	39.1°E	1,875	2,046	71.6	_
31 Jan. 1957	69.0° S	39.1°E	1,869	2,043	71.5	_
l Feb. 1957	69.0° S	39.1°E	1,895	2,058	72.2	_
2 Feb 1957	69.0° S	39.1°E	1,919	2,050	71.8	_
3 Feb 1957	69.0° S	39.1°E	1,909	2,019	70.3	_
4 Feb 1957	69.0° S	39.1°E	1,907	2,009	69.8	_
5 Feb 1957	69.0° S	39.1°E	1,909	1,983	68.5	_
6 Feb 1957	$69.0^{\circ} \mathrm{S}$	39.1°E	1,902	1,984	68.6	_
7 Feb. 1957	69.0° S	39.1°E	1,909	1,915	65.0	_
8 Feb. 1957	69.0° S	39.1°E	1,905	1,888	63.6	_
9 Feb. 1957	69.0° S	39.1°E	1,909	1,884	63.4	-
10 Feb. 1957	69.0° S	39.1°E	1,908	1,861	62.2	_
11 Feb. 1957	69.0° S	39.1°E	1,910	1,919	65.2	_
12 Feb. 1957	69.0° S	39.1°E	1,909	1,932	65.9	_
13 Feb. 1957	69.0° S	39.1°E	1,918	1,945	66.6	_
14 Feb. 1957	69.0° S	39.1°E	-	-		-
15 Feb. 1957	68.8° S	38.9°E	1,886	1,917	65.1	_
16 Feb. 1957	68.4°S	38.8°E	1,892	1,870	62.6	_
17 Feb. 1957	68.4° S	38.7°E	1,908	1,892	63.8	_
18 Feb. 1957	68.4° S	38.7°E	1,890	1,870	62.6	_
1 Mar. 1957	$66.0^{\circ}\mathrm{S}$	33.3°E	1,844	1,804	59.0	_
2 Mar 1957	62.1 ° S	30.3°E	1,866	1,816	59.7	_
3 Mar. 1957	58.5°S	$26.8^{\circ}E$	1,859	1,851	61.6	_
4 Mar. 1957	54.9° S	$25.0^{\circ}\mathrm{E}$	1,868	1,864	62.3	_
5 Mar. 1957	51.6°S	23.7°E	1,859	1,834	60.7	-

Date	Geogr	raphical dinates	(counts	s/2 h)/8	$\begin{array}{c} ln(I_{NPW}) \\ (\%) \end{array}$	$\stackrel{I_{MP}}{(0.01\%)}$
	λ	φ	I _{NP}	I _{NPW}		
6 Mar. 1957	47.1°S	22.9°E	1,914	1,904	64.4	_
7 Mar. 1957	42.6° S	21.7°E	1,897	1,849	61.5	_
8 Mar. 1957	38.4° S	$20.0^{\circ} \mathrm{E}$	1,913	1,867	62.4	_
9 Mar. 1957	34.6° S	18.4°E	1,798	1,811	59.4	_
10 Mar. 1957	33.9°S	18.5°E	1,747	1,771	57.2	_
11 Mar. 1957	33.9°S	18.5°E	1,738	1,779	57.6	_
12 Mar. 1957	33.9°S	18.5°E	1,792	1,781	57.8	_
13 Mar. 1957	33.9°S	18.5°E	1,835	1,807	59.2	_
14 Mar. 1957	33.9°S	18.5°E	1,818	1,797	58.6	_
15 Mar. 1957	34.3°S	18.9°E	1,862	1,834	60.7	_
16 Mar. 1957	34.6° S	23.2°E	1,860	1,859	62.1	_
17 Mar. 1957	33.8°S	28.3°E	1,839	1,843	61.1	_
18 Mar. 1957	32.4° S	33.2°E	1,816	1,818	59.8	_
19 Mar. 1957	$30.7^{\circ}\mathrm{S}$	38.1°E	1,787	1,785	58.0	_
20 Mar. 1957	29.1°S	42.3°E	1,722	1,722	54.3	_
21 Mar. 1957	27.6°S	45.4°E	1,692	1,682	52.0	_
22 Mar. 1957	26.0° S	$48.8^{\circ}E$	1,653	1,641	49.5	_
23 Mar. 1957	24.0°S	52.9°E	1,563	1,549	43.8	_
24 Mar. 1957	21.6° S	57.1°E	1,461	1,444	36.8	_
25 Mar. 1957	19.1°S	61.0°E	1,416	1,398	33.5	_
26 Mar. 1957	16.7°S	64.5°E	1,333	1,316	27.5	_
27 Mar. 1957	$14.0^{\circ}\mathrm{S}$	68.3°E	1,254	1,237	21.3	_
28 Mar. 1957	11.4° S	72.2°E	1,214	1,182	16.7	_
29 Mar. 1957	$8.4^{\circ} S$	75.8°E	1,172	1,162	15.0	_
30 Mar. 1957	5.6°S	79.9°E	1,121	1,122	11.5	_
31 Mar. 1957	2.9°S	84.0°E	1,097	1,093	8.9	_
1 Apr. 1957	0.1° N	87.9°E	1,067	1,064	6.2	_
2 Apr. 1957	3.2°N	91.6°E	1,058	1,046	4.5	_
3 Apr. 1957	$5.5^{\circ}N$	95.5°E	1,043	1,026	2.6	_
4 Apr. 1957	$3.8^{\circ}N$	99.7°E	1,050	1,042	4.1	_
5 Apr. 1957	1.6° N	103.2°E	1,050	1,044	4.3	_
6 Apr. 1957	1.3°N	103.9°E	1,054	1,055	5.4	_
7 Apr. 1957	1.3°N	103.9°E	1,063	1,063	6.1	-
8 Apr. 1957	1.3°N	103.9°E	1,058	1,055	5.4	-
9 Apr. 1957	1.3°N	103.9°E	1,059	1,057	5.5	_
10 Apr. 1957	1.3°N	103.9°E	1,061	1,055	5.4	_
11 Apr. 1957	1.3°N	103.9°E	1,066	1,064	6.2	_
12 Apr. 1957	1.3°N	103.9°E	1,061	1,053	5.2	-
13 Apr. 1957	$2.4^{\circ}N$	104.9°E	1,051	1,041	4.0	-
14 Apr. 1957	$6.0^{\circ} \mathrm{N}$	107.6°E	1,052	1,053	5.2	-
15 Apr. 1957	9.6°N	110.4°E	1,045	1,046	4.5	-
16 Apr. 1957	13.2°N	113.3°E	1,054	1,058	5.6	-
17 Apr. 1957	16.5°N	116.4°E	1,081	1,092	8.8	-
18 Apr. 1957	19.9°N	119.5°E	1,090	1,118	11.2	-
19 Apr. 1957	$23.8^{\circ}N$	$122.8^{\circ}E$	1,141	1,170	15.7	-
20 Apr. 1957	$27.5^{\circ}N$	126.8°E	1,179	1,223	20.1	-
21 Apr. 1957	$31.0^{\circ}N$	131.0°E	1,296	1,338	29.1	-
22 Apr. 1957	$33.2^{\circ}N$	135.7°E	1,347	1,389	32.9	-
23 Apr. 1957	34.5°N	139.0°E	1,403	1,432	35.9	_

 Table A4.1 (Continued)

Run	Site	Latitude	Longitude	Cut-off	Day,	P (mm Hg)	Correcte	d scaled
		(°N)	(°E)	(GV)	1965		rate/	hour
							Neutron	Muon
1	Deep River 1	46.10	282.50	1.02	84	757.4	1,144.7	_
2	Deep River 2	46.10	282.50	1.02	85	753.0	1,191.6	_
5	Ottawa 1	45.40	284.40	1.09	86	763.1	1,083.0	-
4	Arvida	48.43	288.90	0.81	90	754.9	1,174.6	3,159.3
5	Quebec	46.83	288.75	0.96	93	754.2	1,180.4	3,164.7
6	Sherbrooke 1	45.40	288.10	1.11	96	740.9	1,246.1	3,257.6
7	Durham 1	43.10	289.16	1.43	99	755.4	1,162.5	3,156.3
8	New York	40.85	286.07	1.74	103	749.2	1,229.6	3,205.1
9	Swarthmore 1	39.90	284.65	1.89	105	750.7	1,209.6	3,187.6
10	Sterling 1 ^a	38.98	282.53	2.07	108	756.2	1,150.3	3.155.6
11	Greensboro ^a	36.08	280.05	2.65	114	740.0	1,323.9	3,266.1
12	Charleston ^a	32.78	279.97	3.36	117	759.2	1.065.6	3.121.2
13	Jacksonville ^a	30.42	278.35	3.97	120	766.7	9.68.5	3.085.6
14	Mexico City	19.33	260.82	9.83	129	583.3	4,126.3	4.558.5
15	Tres Cumbres	19.12	260.85	9.90	131	549.5	5.668.0	5.007.4
16	Acapulco	16.85	260.13	10.74	132	759.4	744.8	3.013.7
17	Acapulco, Ridge	16.85	260.13	10.74	134	737.9	905.6	3.147.1
18	San Luis ^a Potosi 1	22.18	259.02	8.94	137	612.5	3.285.5	4.271.7
19	Puerto de la Huerta	22.18	259.02	8.94	137	579.3	4.531.2	4.658.3
20	San Luis Potosi 2 ^a	22.18	259.02	8 94	138	612.2	3 285 3	4 282 8
21	Saltville	25.50	259.02	7.35	139	637.0	2.880.3	4,100.8
22	Brownsville ^a	25.90	262 57	6 69	140	759.6	913.9	3 114 2
25	Houston	29.75	264.58	5.04	144	759.5	991.5	3.118.7
24	Dallas	32.78	263.20	4 23	146	739.4	1 243 7	3 271 0
25	Boise City	36.73	257.48	3 53	149	659.7	2 887 8	3 928 8
26	Canon City	38.45	254.77	3 24	149	629.8	3 971 2	4 262 8
20	Saluda	38 55	253.00	3.24	150	591.8	5 874 8	4 732 2
28	Climax	30.33	253.99	3.05	150	505.7	1/ 368 2	6 242 0
20	Leadville	30.23	253.02	3.00	152	523.0	11,007.5	5 874 5
30	Denver 1	39.23	255.00	2.09	152	625.3	1 251 1	1 3 2 1 3
31	Spears 1	30.75	255.00	2.07	155	625.0	3 630 5	ч,521.5
32	Denver 2	39.75	255.00	2.87	155	626.1	4 220 7	4 3 1 3 1
25	Spoore 2	20.75	255.00	2.07	157	624.4	4,220.7	4,515.1
24	Spears 2	39.73 41.02	233.00	2.07	157	024.4	4,233.0	2 2 2 2 0
25	Storling 2ª	41.65	212.33	1.75	164	747.2	1,200.3	3,220.0 2 192 2
26	Sterning 2 Sworthmana 2	20.00	202.33	2.07	164	751.1	1,205.0	2,103.3
30	Swartnmore 2	39.90	284.05	1.89	100	/01./	1,090.7	3,118.3
3/	Kennedy"	40.05	280.22	1.//	108	703.1	1,078.5	-
38	Durnam 2	43.10	289.10	1.43	170	/55.1	1,170.1	3,130.7
39	IVIT. Wash. Koad	44.50	288.70	1.25	1/1	003.3	3,299.3 5,492.2	4,005.6
40	Mt. Wash. Top	44.30	288.70	1.25	1/1	604.2	5,482.2	4,5/4.2
41	Mt. Wash. Base	44.30	288.70	1.25	172	715.9	1,737.6	3,436.1
42	Snerbrooke 2	45.40	288.10	1.11	173	/38.8	1,378.4	3,281.4
45	Ottawa 2	45.40	284.40	1.09	174	751.4	1,149.8	-
44	Deep River 3	46.10	282.50	1.02	175	751.0	1,219.9	3,195.8

Table A4.2 Main results of CR measurements during the latitude survey in summer 1965 (According to Carmichael et al., 1969a)

^a Measurements at airport.

Run	Site	Latitude (°N)	Longitude (°E)	Cut-off (GV)	Day, 1965	P (mm Hg)	Correcte rate/	d scaled hour
							Neutron	Muon
52	Deep River 6	46.10	282.50	1.02	127	749.8	1,228.9	_
53	Deep River 7	46.10	282.50	1.02	127	744.5	1,298.3	-
54	Deep River 8	46.10	282.50	1.02	128	749.1	1,240.2	3,228.5
55	San Francisco ^a	37.62	237.62	4.63	136	763.8	966.0	3,124.5
56	Imperial ^a	32.83	244.43	5.78	139	756.9	984.9	3,150.4
57	Palomar Mt.	33.36	243.14	5.71	140	623.6	3,655.8	4,341.3
58	Dyche Valley	33.29	243.18	5.73	142	646.9	2,893.6	4,082.4
59	Borego ^a	33.25	243.68	5.70	143	743.8	1,123.2	3,247.1
60	Long ^a Valley	37.63	241.15	4.38	145	590.9	5,533.3	4,762.7
61	Klemath Falls ^a	42.17	238.27	3.23	146	655.1	3,102.5	4,013.8
62	Mt. Hood	45.33	238.30	2.43	147	613.4	4,918.5	4,466.6
63	Government Camp	45.30	238.22	2.44	149	667.4	2,794.7	3,861.7
64	Portland ^a	45.58	237.40	2.42	150	761.8	1,078.6	3,137.4
65	Gillums Vineyard	45.38	237.77	2.45	151	732.7	1,441.7	3,324.5
66	Bellingham ^a	48.79	237.46	1.77	152	758.5	1,121.6	3,142.7
67	Grants Pass ^a	42.52	236.62	3.22	154	737.6	1,338.1	3,302.9
68	Creacent City ^a	41.78	235.77	3.49	156	761.5	1,047.3	3,147.9
69	Oakland ^a	37.73	237.80	4.59	158	761.3	995.4	3,145.9
70	Isobe House	20.75	203.70	13.29	178	673.1	1,429.2	-
71	Kula 1	20.73	203.67	13.29	178	686.9	1,252.4	3,359.5
72	Mt. Haleakala	20.71	203.74	13.30	179	533.3	5,242.5	4,891.9
73	Silversword	20.73	203.77	13.29	180	551.2	4,417.7	4,632.2
74	Ranger Station	20.77	203.75	13.28	181	593.6	2,977.7	4,165.9
75	Shangrila	20.77	203.73	13.28	182	615.5	2,417.3	3,947.8
76	Puunene 1	20.83	203.53	13.28	184	760.4	651.3	2,918.9
77	Sugarcane	20.85	203.63	13.27	186	739.7	778.8	3,030.2
78	Puunene 2	20.83	203.53	13.28	187	759.9	653.9	2,921.9
79	Puunene 3	20.83	203.53	13.28	188	760.5	647.3	2,910.8
80	Iao Valley	20.88	203.45	13.27	189	738.4	751.2	-
81	Bineapple	20.83	203.67	13.28	189	718.5	942.5	3,149.2
82	Kula 2	20.73	203.67	13.29	190	685.3	1,277.8	3,388.2
83	Kula 3	20.73	203.67	13.29	197	685.7	1,265.5	3,378.7

Table A4.3 Main results of CR measurements during the latitude survey in May–July 1966 (According to Carmichael et al., 1969b)

^a means measurements at airport.

Run	Site	Cutoff	Air pressure	Corrected data			
		rigidity (GV)	(mm Hg)	reduced to	luced to sea-level		
				sea-le	evel		
				Neutrons (%)	Muons (%)		
1	Deep River 1	1.02	757.4	100.00	-		
2	Deep River 2	1.02	753.0	99.65	—		
3	Ottawa 1	1.09	763.1	100.11	_		
4	Arvida	0.81	754.9	100.09	99.85		
5	Quebec	0.96	754.2	99.89	99.87		
6	Sherbrooke 1	1.11	740.9	99.77	99.95		
7	Durham 1	1.43	755.4	99.56	99.86		
8	New York	1.74	749.2	99.81	100.09		
9	Swarthmore 1	1.89	750.7	98.85	99.87		
10	Sterling 1 ^a	2.07	756.2	99.30	100.00		
11	Greensboro ^a	2.65	740.0	97.32	100.01		
12	Charleston ^a	3.36	759.2	94.77	99.53		
13	Jacksonville ^a	3.97	766.7	92.64	99.93		
14	Mexico City	9.83	583.3	69.63	96.92		
15	Tres Cumbres	9.90	549.5	69.07	96.78		
16	Acapulco	10.74	759.4	66.40	96.15		
17	Acapulco Ridge	10.74	737.9	66.51	96.42		
18	San Luis Potosi 1 ^a	8.94	612.5	72.64	97.59		
19	Puerto de la Huerta	8.94	579.3	72.46	97.21		
20	San Luis Potosi 2 ^a	8.94	612.2	72.43	97.79		
21	Saltville	7.35	637.0	79.17	98.94		
22	Brownsville ^a	6.69	759.6	81.62	99.39		
23	Houston	5.04	759.5	88.46	99.52		
24	Dallas	4.23	739.4	91.21	100.04		
25	Boise City	3.53	659.7	94.76	99.65		
26	Canon City	3.24	629.8	95.57	99.96		
27	Saluda	3.26	591.8	95.51	99.89		
28	Climax	3.05	505.7	96.01	99.94		
29	Leadville	3.09	523.9	96.04	100.06		
30	Denver 1	2.87	625.3	97.10	100.10		
31	Spears 1	2.87	625.9	83.44	_		
32	Denver 2	2.87	626.1	97.20	100.13		
33	Spears 2	2.87	624.4	96.29	_		
34	Chicago	1.73	747.2	99.96	100.41		
35	Sterling 2 ^a	2.07	751.1	98.88	99.82		
36	Swarthmore 2	1.89	761.7	99.43	99.95		
37	Kennedy Airport ^a	1.77	763.1	99.69	_		
38	Durham 2	1.43	755.1	99.91	99.81		
39	Mt. Wash. Road	1.25	653.3	99.99	99.95		
40	Mt. Wash. Top	1.25	604.2	99.84	99.89		
41	Mt. Wash. Base	1.25	715.9	100.09	99.77		
42	Sherbrooke 2	1.11	738.8	100.02	100.23		
43	Ottawa 2	1.09	751.4	94.62	_		
44	Deep River 3	1.02	751.0	99.99	100.19		

Table A4.4 Final results of three Canadian CR latitude surveys in 1965–1966, reduced to sea-level (760 mm Hg). The mean intensity at high latitudes, in the region of the plateau was chosen as 100% (According to Carmichael and Bercovitch, 1969)

Table A4.4 (Co	ontinued)
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Run	Site	Cutoff rigidity (GV)	Air pressure (mm Hg)	Corrected data reduced to sea-level sea-level			
				Neutrons (%)	Muons (%)		
45	Deep River 4	1.02	742.4	99.59	_		
46	Quonset	1.02	748.4	98.44	—		
47	Kapuskasing ^a	0.71	733.9	100.02	_		
48	North Bay ^a	0.95	730.4	100.09	_		
49	Toronto ^a	1.33	743.3	100.08	—		
50	Windsor ^a	1.56	743.1	99.69	—		
51	Deep River 5	1.02	748.1	99.81	—		
52	Deep River 6	1.02	749.8	99.54	—		
53	Deep River 7	1.02	744.5	99.70	_		
54	Deep River 8	1.02	749.1	99.72	100.21		
55	San Francisco ^a	4.63	763.8	89.82	99.99		
56	Imperial ^a	5.78	756.9	85.72	99.40		
57	Palomar Mt.	5.71	623.6	86.21	99.68		
58	Dyche Valley	5.73	646.9	85.91	99.75		
59	Borego ^a	5.70	743.8	86.27	99.68		
60	Long Valley ^a	4.38	590.9	91.28	99.49		
61	Klemath Falls ^a	3.23	655.1	96.81	100.03		
62	Mt. Hood	2.43	613.4	98.99	99.51		
63	Government Camp	2.44	667.4	98.33	99.29		
64	Portland ^a	2.42	761.8	98.42	99.99		
65	Gillums Vineyard	2.45	732.7	98.49	99.62		
66	Bellingham ^a	1.77	758.5	99.06	99.48		
67	Grants Pass ^a	3.22	737.6	96.13	100.03		
68	Creacent City ^a	3.49	761.5	95.29	100.27		
69	Oakland ^a	4.59	761.3	90.36	100.16		
70	Isobe House	13.29	673.1	58.81	—		
71	Kula 1	13.29	686.9	58.44	92.70		
72	Mt. Haleakala	13.30	533.3	58.51	92.79		
73	Silversword	13.29	551.2	58.25	92.37		
74	Ranger Station	13.28	593.6	58.53	92.84		
73	Shangrila	13.28	615.5	58.26	92.83		
76	Puunene 1	13.28	760.4	58.59	92.76		
77	Sugarcane	13.27	739.7	58.44	92.75		
78	Puunene 2	13.28	759.9	58.56	92.76		
79	Puunene 3	13.28	760.5	58.28	92.52		
80	Iao Valley	13.27	738.4	55.70	_		
81	Bineapple	13.28	718.5	58.54	92.57		
82	Kula 2	13.29	685.3	58.79	93.16		
83	Kula 3	13.29	685.7	58.43	92.97		



Fig. A4.1 The average number of counts in a six tube NM-64 calculated for different dead times (According to Bieber et al., 2004)



Fig. A4.2 Time profile plot of the 2000/01 CR latitude survey north-bound voyage. The points show the percentage of counts having $\delta T < 1,200 \,\mu s$. The McMurdo count rate provides an indicator of solar activity during the survey. The effective vertical cutoff rigidity is shown as a solid line. Flat regions of the solid line occur when the ship is moored. The data are hourly averages (According to Bieber et al., 2004)

Appendix to Chapter 5



Fig. A5.1 The 3NM-IQSY neutron super-monitor and two bare counters (2BC neutron detector) used for the Italian latitude survey experiment (two additional spare counters are located on the left wall) (According to Villoresi et al., 2000)

Day	Date	$\lambda\left(^\circ\right)$	$\phi\left(^{\circ}\right)$	R_{cp} (GV)	ΔR_{cp} (GV)	P (mb)	I (3NM)	I (2BC)	Remarks
1	Dec 20, 1006	44.44	10.05	5.20	0.21	1 001 08	0.0710		Damage
1	Dec. 20, 1996	44.44	12.23	5.20	0.21	1,001.98	0.8718	-	Deporturo
2	Dec. 21, 1990	44.40	12.30	6.26	0.25	1,009.44	0.8740	0 702	Maditamanaan Saa
3	Dec. 22, 1990	41.70	21.27	0.20	0.15	1,013.09	0.8285	0.795	Mediterranean Sea
4	Dec. 23, 1996	37.23	21.27	8.01 0.00	0.34	1,015.87	0.7525	0.690	Mediterranean Sea
5	Dec. 24, 1990	31.56	20.88	9.90	0.70	1,010.50	0.6347	0.037	Port Said
7	Dec. 25, 1990	30.06	32 55	11.10	0.79	1,013.97	0.6153	0.559	Suez Channel
0	Dec. 20, 1990	25.65	35.41	12.60	0.02	1,010.25	0.0155	0.502	Pad San
0	Dec. 27, 1990	20.82	28 54	14.01	0.20	1,010.55	0.5400	0.314	Red Sea
9 10	Dec. 28, 1990	16.40	41 15	14.91	0	1,009.75	0.5409	0.488	Red Sea
10	Dec. 29, 1990	12.49	41.15	15.05	0	1,010.45	0.5254	0.473	Indian Ocean
12	Dec. 30, 1990	12.04	40.68	16.18	0	1,015,25	0.5125	0.472	Indian Ocean
12	Jap 01 1007	0.73	54 71	16.13	0	1,013.23	0.5125	0.472	Indian Ocean
13	Jan. 02, 1007	6.78	50.22	16.56	0	1,013.71	0.5020	0.451	Indian Ocean
14	Jan. 02, 1997	2.20	63.00	16.50	0	1,011.01	0.5029	0.431	Indian Ocean
16	Jan. 03, 1997	0.64	68.40	16.27	0	1,011.59	0.5055	0.454	Indian Ocean
17	Jan. 05, 1997	-0.04	72.49	15.74	0	1,010.55	0.5055	0.434	Indian Ocean
19	Jan. 05, 1997	-4.03	78.02	14.00	0	1,010.40	0.51/0	0.470	Indian Ocean
10	Jan. 07, 1997	12.02	82.66	14.90	0	1,006.56	0.5543	0.404	Indian Ocean
20	Jan. 07, 1997	-12.02	87.20	12.07	0	1,000.79	0.5345	0.499	Indian Ocean
20	Jan. 00, 1997	-13.02	01.29	12.07	0 10	1,007.49	0.5679	0.531	Indian Ocean
21	Jan. 10, 1997	-18.93	91.71	0.13	0.19	1,007.78	0.0348	0.582	Indian Ocean
22	Jan. 10, 1997	-22.39	101 47	9.13 6.76	0.30	1,011.09	0.7141	0.071	Indian Ocean
23	Jan. 12, 1997	-23.80	101.47	5.28	0.19	1,010.02	0.8037	0.705	Indian Ocean
24	Jan. 12, 1997	22.30	111 81	3.20	0.31	1,019.40	0.0742	0.041	Indian Ocean
25	Jan. 13, 1997	- 32.83	111.01	3.97	0.33	1,020.14	0.9344	0.911	South Ocean
20	Jan. 14, 1997	-37.82	125.02	2.46	0.29	1,020.20	0.9019	0.939	South Ocean
28	Jan. 15, 1997	20.02	122.02	2.40	0.20	1,022.11	0.9790	0.909	South Ocean
20	Jan. 10, 1997	-39.92	132.20	2.08	0.23	1,025.75	0.9907	0.985	South Ocean
30	Jan 18 1007	-43.25	146.40	1.77	0.10	1,024.11	0.0030	0.985	Hobart
31	Jan 10, 1997	-42.88	140.40	1.04	0.22	1,022.35	0.9950	0.980	Hobart
32	Jan. 20, 1007	42.00	150.35	1.72	0.23	1,015.50	0.0026	0.081	Departure
32	Jan 21 1007	-45.07	158.30	1.70	0.16	1,007.04	0.9920	0.981	Pacific Ocean
3/	Jan 22, 1997	-46.33	166 35	1.00	0.10	1,009.94	1.0022	1.010	Pacific Ocean
35	Jan 23 1997	-44 35	172 30	2.29	0.10	1,024.15	0.9851	1.010	I vttelton
36	Ian 24 1997	-43.61	172.30	2.53	0.19	1 014 00	0.9771	_	Lyttelton
37	Jan 25 1997	-43.67	172.72	2.55	0.16	1,020,00	0.9764	_	Departure
38	Jan 26 1997	-47.18	174.02	1 77	0.10	1,026.00	0.9969	0.992	Pacific Ocean
30	Jan 27 1997	-52.63	175.46	1.01	0.09	1,020.72	1 0024	1.003	Pacific Ocean
40	Jan 28 1997	-58.29	177.07	0.55	0	1,027.30	0.9980	0.991	Pacific Ocean
41	Jan 20, 1997	-63.72	179.26	0.09	0	981.45	1.0018	1 000	Pacific Ocean
42	Jan 30 1997	-67.19	180.57	0.05	0	988.09	1.0010	1.000	Pacific Ocean
43	Jan 31 1997	-70.12	177 41	0.00	0	998 71	1.0172	1.022	Pacific Ocean
44	Feb 01 1997	-74.08	168.89	0.0043	0	1 001 62	0.9935	0.992	Pacific Ocean
45	Feb 02 1997	-74.69	164.07	0.0031	0	1,001.02	0.9977	-	Antarc (BTN)
46	Feb 03 1997	-74 72	164 17	0.0030	0	1 002 50	0.9953	_	Antarc (BTN)
47	Feb 04 1997	-74 72	164 13	0.0030	0	998.68	0 9984	_	Antarc (BTN)
48	Feb 05 1997	_74 74	164.26	0.0030	0	997 34	1 0051	_	Antarc (BTN)
49	Feb 06 1997	-74 77	164 32	0.0029	0	995 72	0 9948	_	Antarc (BTN)
50	Feb. 07, 1997	-74.75	164.27	0.0030	0	991.82	1.0005	_	Antarc.(BTN)
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 Table A5.1 Daily averages of the survey data (According to Villoresi et al., 2000)

Day	Date	$\lambda\left(^{\circ}\right)$	$\phi\left(^{\circ}\right)$	R_{cp} (GV)	ΔR_{cp} (GV)	P (mb)	I (3NM)	I (2BC)	Remarks
51	Feb. 08, 1997	-74.77	164.52	0.0029	0	990.92	0.9996	-	Antarc.(BTN)
52	Feb. 09, 1997	-74.80	164.63	0.0029	0	993.29	0.9992	-	Antarc.(BTN)
53	Feb. 10, 1997	-74.76	164.30	0.0029	0	993.73	1.0050	_	Antarc.(BTN)
54	Feb. 11, 1997	-74.75	164.30	0.0030	0	996.87	1.0004	_	Antarc.(BTN)
55	Feb. 12, 1997	-74.71	164.27	0.0030	0	994.74	1.0023	_	Antarc.(BTN)
56	Feb. 13, 1997	-73.72	169.84	0.0052	0	985.37	1.0080	_	Departure
57	Feb. 14, 1997	-68.58	173.48	0.0400	0	988.11	0.9923	0.995	Pacific Ocean
58	Feb. 15, 1997	-63.28	173.58	0.16	0	987.82	0.9915	0.993	Pacific Ocean
59	Feb. 16, 1997	-60.29	173.11	0.33	0	972.71	0.9934	0.993	Pacific Ocean
60	Feb. 17, 1997	-57.57	170.46	0.44	0	998.93	0.9992	1.000	Pacific Ocean
61	Feb. 18, 1997	-52.04	170.45	0.95	0.07	1,011.86	0.9976	0.986	Pacific Ocean
62	Feb. 19, 1997	-46.45	171.69	1.84	0.18	1,013.39	0.9861	0.971	Pacific Ocean
63	Feb. 20, 1997	-43.61	172.75	2.51	0.21	1,002.38	0.9723	-	Lyttelton
64	Feb. 21, 1997	-43.61	172.72	2.52	0.20	1,001.87	0.9705	-	Lyttelton
65	Feb. 22, 1997	-42.90	173.33	2.80	0.21	997.83	0.9709	0.950	Departure
66	Feb. 23, 1997	-40.30	171.09	3.31	0.21	1,006.13	0.9488	0.924	Pacific Ocean
67	Feb. 24, 1997	-39.92	163.77	2.96	0.37	1,003.62	0.9551	0.933	Pacific Ocean
68	Feb. 25, 1997	-39.58	157.17	2.86	0.31	1,005.03	0.9683	0.952	Pacific Ocean
69	Mar. 01, 1997	-36.92	129.37	2.80	0.34	1,016.00	0.9701	0.964	South. Ocean
70	Mar. 02, 1997	-36.14	123.25	2.93	0.36	1,019.54	0.9626	0.950	South. Ocean
71	Mar. 03, 1997	-34.86	116.21	3.34	0.21	1,023.04	0.9616	0.948	South. Ocean
72	Mar. 04, 1997	-31.63	110.47	4.49	0.36	1,015.29	0.9067	0.880	Indian Ocean
73	Mar. 05, 1997	-28.09	105.13	5.72	0.28	1,013.78	0.8468	0.810	Indian Ocean
74	Mar. 06, 1997	-24.47	99.94	7.60	0.24	1,016.70	0.7691	0.729	Indian Ocean
75	Mar. 07, 1997	-20.92	95.02	10.14	0.24	1,016.22	0.6747	0.625	Indian Ocean
76	Mar. 08, 1997	-17.36	90.29	12.11	0.07	1,012.85	0.6093	0.558	Indian Ocean
77	Mar. 09, 1997	-13.81	85.61	13.52	0	1,011.67	0.5680	0.518	Indian Ocean
78	Mar. 10, 1997	-10.13	80.93	14.60	0	1,012.04	0.5398	0.486	Indian Ocean
79	Mar. 11, 1997	-6.56	76.32	15.41	0	1,012.34	0.5229	0.471	Indian Ocean
80	Mar. 12, 1997	-3.05	71.73	15.99	0	1,011.45	0.5106	0.459	Indian Ocean
81	Mar. 13, 1997	0.30	66.87	16.33	0	1,009.89	0.5045	0.451	Indian Ocean
82	Mar. 14, 1997	4.26	62.05	16.55	0	1,009.29	0.4995	0.447	Indian Ocean
83	Mar. 15, 1997	7.66	57.48	16.53	0	1,010.65	0.5012	0.450	Indian Ocean
84	Mar. 16, 1997	10.99	52.90	16.34	0	1,010.84	0.5047	0.454	Indian Ocean
85	Mar. 17, 1997	12.44	47.76	16.09	0	1,009.57	0.5125	0.463	Indian Ocean
86	Mar. 18, 1997	13.84	42.95	15.85	0	1,011.91	0.5165	0.470	Red Sea
87	Mar. 19, 1997	18.25	40.11	15.34	0	1,012.80	0.5301	0.493	Red Sea
88	Mar. 20, 1997	23.11	37.10	14.42	0	1,012.17	0.5526	0.520	Red Sea
89	Mar. 21, 1997	28.08	33.68	12.73	0.36	1,008.20	0.5914	0.558	Suez
90	Mar. 22, 1997	30.81	32.25	11.47	0.69	1,011.55	0.6290	0.602	Suez Channel
91	Mar. 23, 1997	33.27	28.40	10.09	1.07	1,013.56	0.6703	0.643	Mediterranean Sea
92	Mar. 24, 1997	36.09	22.57	9.27	0.52	1,012.31	0.7108	0.687	Mediterranean Sea
93	Mar. 25, 1997	40.46	18.20	6.84	0.27	1,009.51	0.8002	0.777	Mediterranean Sea
94	Mar. 26, 1997	43.67	13.81	5.50	0.15	1,017.27	0.8572	-	Ravenna

 λ – geographic latitude; φ – geographic longitude; R_{cp} – vertical cutoff rigidity corrected for penumbra; ΔR_{cp} – penumbra effect (see Chapter 3); P – atmospheric pressure; I, 3NM and I, 2BC – normalized intensities of 3NM-IQSY and 2BC detectors; BTN denotes Baia Terra Nova, the Italian Antarctic Base.

Day	Latitude	Longitude	$\theta = 0^{\circ}$		φ =	= 0°		$\varphi = 45^{\circ}$				
of year				$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = I45^{\circ}$	$\theta = 60^{\circ}$	
355	44.443°	12.247°	5.15	5.10	5.11	5.66	5.06	5.34	5.65	5.85	6.46	
356	44.402°	12.382°	5.19	5.14	5.17	5.34	5.04	5.36	5.73	5.85	6.50	
357	41.757°	16.556°	6.26	6.08	6.08	6.08	6.79	6.46	6.79	7.14	7.59	
358	37.250°	21.264°	8.61	8.78	8.01	7.73	7.96	9.58	10.27	9.66	10.03	
359	33.857°	26.881°	9.89	10.70	11.18	9.21	9.22	11.36	12.93	16.20	13.14	
360	31.557°	31.921°	11.10	11.05	12.42	12.15	9.93	12.29	13.36	18.55	22.40	
361	30.061°	32.548°	11.82	12.16	11.65	14.25	10.40	13.64	16.31	19.63	24.03	
362	25.651°	35.413°	13.78	14.45	15.41	16.12	17.66	15.72	18.36	22.05	27.33	
363	20.816°	38.544°	14.91	15.56	16.62	18.12	19.98	16.97	19.82	23.85	29.69	
364	16.493°	41.145°	15.58	16.18	17.22	18.76	20.86	17.70	20.67	24.89	31.03	
365	12.844°	44.252°	15.95	16.49	17.49	19.03	21.17	18.09	21.12	25.43	31.75	
366	12.239°	49.683°	16.18	16.72	17.75	19.31	21.51	18.35	21.42	25.80	32.21	
1	9.728°	54.710°	16.43	16.94	17.93	19.48	21.69	18.62	21.71	26.15	32.66	
2	6.278°	59.323°	16.56	16.99	17.90	19.38	21.51	18.71	21.79	26.23	32.76	
3	2.820°	63.900°	16.50	16.84	17.65	19.00	20.98	18.59	21.60	25.96	32.42	
4	-0.640°	68.490°	16.26	16.49	17.16	18.33	20.08	18.25	21.14	25.35	31.62	
5	-4.629°	73.476°	15.74	15.81	16.29	17.19	18.54	17.56	20.23	24.18	30.09	
6	-8.788°	78.023°	14.90	14.81	15.04	15.58	16.39	16.48	18.87	22.42	27.77	
7	-12.023°	82.657°	14.06	13.83	13.84	14.05	14.34	15.42	17.50	20.62	25.36	
8	-15.623°	87.286°	12.86	12.49	12.27	12.12	11.90	13.93	15.58	18.07	21.85	
9	-18.933°	91.709°	11.24	10.85	10.57	10.22	9.88	12.12	13.36	14.99	17.24	
10	-22.386°	96.410°	9.18	8.90	8.72	8.48	8.37	9.72	10.24	10.62	10.51	
11	-25.862°	101.473°	6.72	6.89	6.95	6.93	6.99	7.15	7.52	7.77	8.04	
12	-29.376°	106.587°	5.19	5.28	5.35	5.37	5.24	5.61	5.87	6.13	6.35	
13	-32.825°	111.807°	4.00	4.01	3.98	3.93	3.94	4.11	4.27	4.29	4.37	
14	-35.707°	118.051°	3.08	3.09	3.04	3.02	3.02	3.20	3.31	3.47	3.43	
15	-37.818°	125.015°	2.52	2.51	2.55	2.57	2.52	2.60	2.67	2.73	2.76	
16	-39.920°	132.276°	2.08	2.11	2.14	2.08	2.16	2.17	2.21	2.18	2.31	
17	-42.036°	139.765°	1.76	1.80	1.80	1.78	1.83	1.83	1.83	1.88	1.90	
18	-43.250°	146.398°	1.72	1.62	1.70	1.63	1.67	1.76	1.75	1.77	1.80	
19	-42.881°	147.341°	1.73	1.77	1.76	1.73	1.82	1.83	1.85	1.88	1.84	
20	-43.701°	150.347°	1.66	1.69	1.68	1.73	1.69	1.72	1.76	1.80	1.76	
21	-45.069°	158.389°	1.67	1.67	1.62	1.73	1.64	1.70	1.70	1.71	1.75	
22	-46.325°	166.352°	1.70	1.70	1.66	1.72	1.68	1.76	1.74	1.77	1.79	
23	-44.349°	172.300°	2.29	2.34	2.32	2.31	2.35	2.43	2.46	2.53	2.60	
24	-43.606°	172.720°	2.53	2.56	2.54	2.53	2.50	2.65	2.64	2.68	2.65	
25	-43.672°	172.823°	2.53	2.54	2.58	2.54	2.47	2.61	2.67	2.67	2.65	
26	-47.179°	174.023°	1.83	1.82	1.81	1.80	1.79	1.89	1.93	2.00	1.93	
27	-52.628°	175.464°	0.98	0.99	0.98	0.99	1.00	1.03	1.01	1.05	1.05	

Day		$arphi=90^\circ$				$\varphi = 135^{\circ}$				$arphi=180^\circ$			
of year	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$	$\overline{\theta = 15^{\circ}}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$	
355	5.55	5.96	6.29	6.75	5.49	5.72	6.01	6.14	5.18	5.31	5.33	5.36	
356	5.55	5.93	6.37	6.84	5.43	5.73	6.00	6.14	5.18	5.27	5.27	5.39	
357	6.73	7.27	7.75	8.30	6.67	7.05	7.31	7.59	6.38	6.34	6.39	6.35	
358	9.82	11.45	13.89	17.08	9.25	10.00	10.76	11.30	8.55	8.32	8.22	8.09	
359	11.26	13.12	17.49	22.76	10.80	12.17	13.67	15.69	9.86	9.95	9.78	9.59	
360	12.76	15.99	19.84	25.54	12.05	13.31	15.54	18.04	10.93	10.97	10.82	10.67	
361	13.96	16.96	20.94	27.01	12.84	14.56	16.59	19.46	11.58	11.62	11.52	11.42	
362	15.94	19.05	23.62	30.55	14.92	16.63	19.17	22.92	13.40	13.26	13.35	13.62	
363	17.30	20.74	25.77	33.37	16.26	18.30	21.31	25.74	14.61	14.64	15.01	15.69	
364	18.13	21.77	27.08	35.09	17.11	19.37	22.67	27.51	15.38	15.56	16.14	17.12	
365	18.60	22.35	27.82	36.06	17.60	20.00	23.47	28.54	15.83	16.12	16.84	18.02	
366	18.86	22.67	28.21	36.55	17.85	20.28	23.81	28.96	16.06	16.35	17.07	18.25	
1	19.17	23.06	28.69	37.15	18.18	20.70	24.34	29.64	16.37	16.73	17.54	18.82	
2	19.33	23.25	28.92	37.43	18.38	20.99	24.72	30.14	16.58	17.03	17.96	19.39	
3	19.27	23.18	28.83	37.27	18.38	21.05	24.83	30.30	16.61	17.17	18.19	19.74	
4	18.99	22.83	28.38	36.66	18.18	20.87	24.66	30.11	16.47	17.11	18.23	19.87	
5	18.36	22.07	27.43	35.41	17.68	20.34	24.08	29.42	16.06	16.79	17.98	19.65	
6	17.36	20.85	25.92	33.46	16.80	19.40	23.00	28.10	15.33	16.12	17.31	18.88	
7	16.34	19.62	24.38	31.50	15.92	18.42	21.87	26.71	14.57	15.40	16.53	17.83	
8	14.88	17.83	22.18	28.72	14.60	16.93	20.10	24.48	13.39	13.97	15.04	10.96	
9	13.06	15.66	19.48	25.34	12.82	15.00	17.70	21.20	11.68	12.37	11.01	9.42	
10	10.37	12.07	14.73	19.18	10.06	10.66	9.60	10.00	9.08	8.21	7.88	8.25	
11	7.23	7.68	8.17	8.83	6.97	7.23	7.63	8.30	6.57	6.56	6.72	6.97	
12	5.56	6.07	6.35	7.02	5.53	5.82	6.12	6.08	5.26	5.27	5.28	5.08	
13	4.22	4.34	4.51	4.65	4.05	4.19	4.33	4.55	3.87	3.95	3.92	4.10	
14	3.27	3.36	3.66	3.56	3.18	3.42	3.29	3.42	3.11	3.06	3.02	3.08	
15	2.56	2.69	2.82	2.87	2.58	2.62	2.66	2.74	2.51	2.52	2.50	2.56	
16	2.18	2.24	2.30	2.33	2.20	2.15	2.18	2.28	2.13	2.08	2.23	2.08	
17	1.83	1.90	1.96	1.88	1.86	1.89	1.87	1.91	1.83	1.75	1.86	1.83	
18	1.70	1.78	1.78	1.88	1.77	1.78	1.80	1.81	1.71	1.71	1.74	1.68	
19	1.88	1.89	1.94	1.99	1.83	1.94	1.82	1.97	1.84	1.77	1.92	1.83	
20	1.75	1.79	1.83	1.91	1.72	1.79	1.79	1.83	1.68	1.70	1.71	1.72	
21	1.75	1.79	1.74	1.86	1.74	1.74	1.77	1.80	1.69	1.70	1.71	1.68	
22	1.77	1.82	1.84	1.89	1.77	1.80	1.82	1.84	1.75	1.70	1.86	1.82	
23	2.45	2.50	2.58	2.87	2.44	2.51	2.74	2.61	2.38	2.55	2.41	2.41	
24	2.69	2.76	2.84	2.84	2.67	2.72	2.74	3.03	2.61	2.55	2.69	2.60	
25	2.66	2.77	2.81	2.80	2.63	2.74	2.80	2.89	2.56	2.55	2.67	2.63	
26	1.91	1.88	2.01	1.99	1.86	1.95	1.95	2.02	1.86	1.90	1.86	1.89	
27	1.03	1.05	1.12	1.06	1.02	1.08	1.04	1.09	1.01	1.02	1.05	1.04	

Table A5.3 The same as in Table A5.2, but for azimuth angles $\varphi = 90^{\circ}$, 135°, and 180° of CR incident particles
Day	$\varphi = 225^{\circ}$			$arphi=270^\circ$				$\varphi = 315^{\circ}$				
of year	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$
355	4.93	4.69	4.50	4.38	4.85	4.52	4.37	4.31	4.90	4.80	4.91	4.37
356	4.95	4.79	4.55	4.42	4.87	4.56	4.36	4.28	4.92	4.74	4.91	4.42
357	5.99	5.74	5.49	5.26	5.75	5.35	5.05	4.91	5.85	5.58	5.36	5.36
358	7.94	7.45	7.15	6.86	7.94	7.30	6.76	6.13	8.11	7.22	6.70	6.59
359	9.12	8.50	8.09	7.84	8.81	8.31	7.67	7.85	9.68	9.19	8.07	7.51
360	10.14	9.44	8.88	8.57	10.00	9.08	8.19	8.22	10.25	9.97	9.86	8.12
361	10.73	9.97	9.34	8.96	10.59	9.66	8.99	8.19	11.00	9.86	10.19	8.89
362	12.26	11.33	10.58	10.07	12.07	11.00	10.30	9.85	12.86	12.27	11.33	10.52
363	13.41	12.32	11.55	11.00	13.22	12.01	11.14	10.65	14.06	13.54	13.27	13.02
364	14.05	12.97	12.22	11.74	13.77	12.49	11.61	11.06	14.59	14.03	13.80	13.78
365	14.43	13.37	12.66	12.25	14.06	12.72	11.78	11.16	14.86	14.21	13.92	13.89
366	14.63	13.55	12.84	12.41	14.26	12.89	11.94	11.31	15.07	14.41	14.11	14.13
1	14.89	13.83	13.14	12.76	14.47	13.07	12.08	11.41	15.26	14.54	14.18	14.13
2	15.06	14.05	13.43	13.13	14.57	13.14	12.12	11.43	15.31	14.50	14.05	13.88
3	15.07	14.14	13.60	13.39	14.52	13.09	12.07	11.39	15.19	14.30	13.74	13.45
4	14.93	14.09	13.65	13.54	14.31	12.91	11.93	11.28	14.89	13.93	13.28	12.86
5	14.55	13.84	13.51	13.51	14.55	12.55	11.64	11.08	14.33	13.30	12.56	12.02
6	13.89	13.32	13.10	12.07	13.89	11.96	11.17	10.65	13.48	12.42	11.63	11.04
7	13.21	12.66	12.02	12.39	13.13	11.37	10.54	10.09	12.67	11.62	10.84	10.27
8	11.86	11.11	11.07	10.64	11.43	10.30	9.55	9.05	11.52	10.54	9.86	9.43
9	10.62	10.30	9.16	7.73	10.05	9.28	8.65	8.42	10.14	9.38	8.72	8.58
10	8.50	7.48	6.80	6.81	8.37	7.73	7.02	6.28	8.44	7.88	7.59	7.36
11	6.31	5.98	5.89	5.80	6.28	5.78	5.43	5.42	6.51	6.31	6.01	5.74
12	5.04	4.90	4.83	4.43	4.96	4.75	4.56	4.51	5.09	4.85	4.68	4.61
13	3.78	3.67	3.65	3.53	3.82	3.57	3.50	3.38	3.87	3.86	3.70	3.45
14	3.01	2.91	2.82	2.77	2.97	2.92	2.74	2.74	3.05	2.90	2.83	2.91
15	2.48	2.42	2.39	2.37	2.42	2.38	2.36	2.23	2.46	2.39	2.36	2.31
16	2.09	2.03	2.02	2.02	2.03	2.00	1.92	1.92	2.11	2.03	2.02	1.91
17	1.81	1.71	1.71	1.69	1.75	1.71	1.64	1.62	1.74	1.70	1.68	1.70
18	1.66	1.63	1.60	1.58	1.67	1.59	1.62	1.61	1.66	1.65	1.61	1.58
19	1.80	1.73	1.70	1.71	1.74	1.70	1.65	1.60	1.75	1.74	1.67	1.63
20	1.69	1.63	1.60	1.56	1.67	1.60	1.57	1.61	1.70	1.63	1.56	1.60
21	1.66	1.63	1.60	1.59	1.65	1.56	1.58	1.58	1.68	1.61	1.53	1.58
22	1.72	1.67	1.62	1.62	1.67	1.63	1.60	1.66	1.70	1.67	1.59	1.61
23	2.32	2.33	2.23	2.25	2.27	2.32	2.17	2.18	2.30	2.21	2.28	2.13
24	2.53	2.46	2.36	2.54	2.46	2.31	2.37	2.29	2.51	2.43	2.39	2.40
25	2.52	2.47	2.37	2.41	2.43	2.33	2.38	2.23	2.48	2.45	2.36	2.47
26	1.84	1.80	1.83	1.82	1.81	1.77	1.74	1.64	1.78	1.73	1.76	1.66
27	1.01	1.00	1.00	0.98	1.01	0.96	0.96	0.97	1.00	1.00	0.95	0.97

Table A5.4 The same as in Table A5.2, but for azimuth angles $\varphi = 225^{\circ}$, 270°, and 315° of CR incident particles

Table A5.5 Effective cutoff rigidities (in GV) computed along the survey from Italy to Antarctica for different zenith angles $\theta = 0^{\circ}$, 15° , 30° , 45° , 60° for azimuth angles $\varphi = 0^{\circ}$ and 45° of CR incident particles for days 48–56 and 60–85 of 1997 (CR data for three days 57–59 of 1997 are not available because of very bad storm weather)

Day 1997	Latitude	Longitude	$\theta = 0^{\circ}$	$arphi = 0^\circ \ heta \ heta$			$arphi=45^\circ$ $ heta$				
				15°	30°	45°	60°	15°	30°	45°	60°
48	-57.565	170.462	0.40	0.45	0.39	0.38	0.37	0.39	0.41	0.38	0.40
49	-52.037	170.453	0.94	0.95	0.95	0.90	0.91	0.93	0.95	0.96	0.94
50	-46.451	171.694	1.86	1.89	1.89	1.83	1.77	1.91	1.97	2.00	1.99
51	-43.607	172.751	2.55	2.54	2.55	2.57	2.47	2.66	2.63	2.70	2.67
52	-43.607	172.723	2.56	2.52	2.55	2.56	2.49	2.63	2.66	2.69	2.71
53	-42.904	173.329	2.83	2.74	2.70	2.64	2.79	2.86	2.90	2.92	2.95
54	-40.298	171.086	3.36	3.33	3.33	3.29	3.22	3.46	3.54	3.59	3.69
55	-39.919	163.772	3.09	3.07	3.05	3.04	3.00	3.17	3.20	3.40	3.38
56	-39.584	157.170	2.95	2.86	2.84	2.86	2.76	2.98	3.02	3.12	3.08
60	-36.924	129.369	2.86	2.84	2.77	2.79	2.76	2.91	2.99	3.02	3.08
61	-36.137	123.245	2.93	2.96	3.03	2.94	2.93	3.13	3.20	3.27	3.22
62	-34.861	116.206	3.35	3.34	3.39	3.35	3.23	3.43	3.54	3.65	3.82
63	-31.632	110.474	4.50	4.44	4.36	4.32	4.34	4.73	4.85	5.03	4.86
64	-28.092	105.127	5.75	5.84	5.88	5.91	6.06	6.09	6.35	6.67	7.03
65	-24.472	99.935	7.57	7.67	7.59	7.55	7.50	8.08	8.40	8.62	8.81
66	-20.922	95.022	10.12	9.81	9.50	9.17	8.98	10.82	11.64	12.59	13.16
67	-17.358	90.285	12.12	11.71	11.42	11.13	10.76	13.09	14.47	16.55	19.64
68	-13.805	85.611	13.52	13.21	13.09	13.11	13.11	14.73	16.60	19.43	23.72
69	-10.133	80.926	14.60	14.44	14.57	14.97	15.55	16.09	18.34	21.71	26.81
70	-6.557	76.324	15.41	15.40	15.76	16.50	17.60	17.12	19.66	23.44	29.10
71	-3.051	71.732	15.99	16.12	16.67	17.69	19.21	17.87	20.64	24.71	30.77
72	0.301	66.867	16.33	16.59	17.30	18.53	20.34	18.35	21.27	25.54	31.88
73	4.256	62.045	16.55	16.92	17.78	19.19	21.24	18.67	21.71	26.11	32.62
74	7.656	57.482	16.53	16.99	17.94	19.44	21.62	18.70	21.79	26.23	32.77
75	10.992	52.902	16.34	16.87	17.88	19.44	21.66	18.53	21.62	26.03	32.51
76	12.439	47.758	16.09	16.64	17.65	19.20	21.38	18.26	21.31	25.66	32.04
77	13.844	42.947	15.85	16.40	17.41	18.95	21.08	17.99	20.99	25.28	31.55
78	18.252	40.105	15.34	15.96	17.01	18.55	20.59	17.44	20.37	24.52	30.56
79	23.111	37.100	14.42	15.10	16.15	17.57	19.14	16.43	19.19	23.08	28.69
80	28.076	33.680	12.72	13.38	14.06	15.05	11.17	14.83	17.38	20.82	25.69
81	30.812	32.253	11.48	11.58	12.78	13.49	10.15	12.99	15.58	19.11	23.27
82	33.270	28.403	10.19	10.87	11.71	9.61	9.40	11.05	14.00	16.88	15.12
83	36.094	22.574	9.23	9.52	8.97	8.51	8.38	10.19	11.65	11.69	11.11
84	40.463	18.202	6.87	6.68	6.57	6.59	6.68	7.16	7.34	7.75	8.28
85	43.666	13.806	5.44	5.36	5.46	5.30	5.36	5.72	5.91	6.23	6.66

Day 1997		$arphi=90^\circ$ $ heta$								$arphi=180^\circ$ $ heta$			
	15°	30°	45°	60°	15°	30°	45°	60°	15°	30°	45°	60°	
48	0.38	0.40	0.41	0.41	0.41	0.41	0.38	0.40	0.41	0.41	0.41	0.41	
49	0.97	0.95	0.93	0.93	0.93	0.93	0.97	0.95	0.93	0.93	0.93	0.93	
50	1.95	2.02	1.89	1.89	1.89	1.89	1.95	2.02	1.89	1.89	1.89	1.89	
51	2.64	2.73	2.60	2.60	2.60	2.60	2.64	2.73	2.60	2.60	2.60	2.60	
52	2.61	2.75	2.56	2.56	2.56	2.56	2.61	2.75	2.56	2.56	2.56	2.56	
53	2.93	3.06	2.77	2.77	2.77	2.77	2.93	3.06	2.77	2.77	2.77	2.77	
54	3.51	3.67	3.44	3.44	3.44	3.44	3.51	3.67	3.44	3.44	3.44	3.44	
55	3.21	3.33	3.19	3.19	3.19	3.19	3.21	3.33	3.19	3.19	3.19	3.19	
56	3.06	3.20	2.99	2.99	2.99	2.99	3.06	3.20	2.99	2.99	2.99	2.99	
60	3.01	3.05	2.85	2.85	2.85	2.85	3.01	3.05	2.85	2.85	2.85	2.85	
61	3.10	3.35	3.08	3.08	3.08	3.08	3.10	3.35	3.08	3.08	3.08	3.08	
62	3.48	3.65	3.36	3.36	3.36	3.36	3.48	3.65	3.36	3.36	3.36	3.36	
63	4.78	5.17	4.61	4.61	4.61	4.61	4.78	5.17	4.61	4.61	4.61	4.61	
64	6.06	6.62	5.69	5.69	5.69	5.69	6.06	6.62	5.69	5.69	5.69	5.69	
65	8.23	8.79	7.31	7.31	7.31	7.31	8.23	8.79	7.31	7.31	7.31	7.31	
66	11.62	13.89	10.55	10.55	10.55	10.55	11.62	13.89	10.55	10.55	10.55	10.55	
67	14.03	16.77	12.41	12.41	12.41	12.41	14.03	16.77	12.41	12.41	12.41	12.41	
68	15.67	18.80	14.07	14.07	14.07	14.07	15.67	18.80	14.07	14.07	14.07	14.07	
69	16.98	20.39	15.07	15.07	15.07	15.07	16.98	20.39	15.07	15.07	15.07	15.07	
70	16.71	21.58	15.79	15.79	15.79	15.79	16.71	21.58	15.79	15.79	15.79	15.79	
71	18.66	22.43	16.26	16.26	16.26	16.26	18.66	22.43	16.26	16.26	16.26	16.26	
72	19.07	22.93	16.51	16.51	16.51	16.51	19.07	22.93	16.51	16.51	16.51	16.51	
73	19.32	23.24	16.62	16.62	16.62	16.62	19.32	23.24	16.62	16.62	16.62	16.62	
74	19.29	23.20	16.51	16.51	16.51	16.51	19.29	23.20	16.51	16.51	16.51	16.51	
75	19.06	22.91	16.24	16.24	16.24	16.24	19.06	22.91	16.24	16.24	16.24	16.24	
76	18.76	22.55	15.97	15.97	15.97	15.97	18.76	22.55	15.97	15.97	15.97	15.97	
77	18.47	22.20	15.71	15.71	15.71	15.71	18.47	22.20	15.71	15.71	15.71	15.71	
78	17.83	21.40	15.09	15.09	15.09	15.09	17.83	21.40	15.09	15.09	15.09	15.09	
79	16.71	20.00	14.07	14.07	14.07	14.07	16.71	20.00	14.07	14.07	14.07	14.07	
80	15.07	17.96	12.42	12.42	12.42	12.42	15.07	17.96	12.42	12.42	12.42	12.42	
81	13.39	16.54	11.25	11.25	11.25	11.25	13.39	16.54	11.25	11.25	11.25	11.25	
82	11.56	14.97	10.12	10.12	10.12	10.12	11.56	14.97	10.12	10.12	10.12	10.12	
83	10.51	12.30	9.06	9.06	9.06	9.06	10.51	12.30	9.06	9.06	9.06	9.06	
84	7.46	8.21	7.02	7.02	7.02	7.02	7.46	8.21	7.02	7.02	7.02	7.02	
85	5.90	6.25	5.51	5.51	5.51	5.51	5.90	6.25	5.51	5.51	5.51	5.51	

Table A5.6 The same as in Table A5.5, but for azimuth angles $\varphi = 90^{\circ}$, 135° , and 180°

Day 1997						$arphi=270^\circ$ $ heta$				$arphi = 315^{\circ}$ $ heta$			
	15°	30°	45°	60°	15°	30°	45°	60°	15°	30°	45°	60°	
48	0.40	0.36	0.36	0.37	0.37	0.37	0.39	0.39	0.40	0.38	0.39	0.34	
49	0.93	0.93	0.94	0.91	0.94	0.90	0.87	0.87	0.93	0.91	0.91	0.90	
50	1.88	1.85	1.82	1.81	1.76	1.86	1.73	1.73	1.82	1.76	1.83	1.70	
51	2.53	2.49	2.37	2.45	2.51	2.36	2.37	2.28	2.51	2.42	2.37	2.41	
52	2.49	2.48	2.34	2.51	2.47	2.35	2.38	2.30	2.52	2.42	2.38	2.40	
53	2.73	2.64	2.76	2.59	2.68	2.57	2.55	2.38	2.73	2.66	2.51	2.47	
54	3.28	3.30	3.05	3.18	3.21	3.07	3.04	2.95	3.21	3.13	3.05	3.10	
55	3.09	2.97	2.88	2.84	2.98	3.00	2.75	2.77	2.99	2.84	2.87	2.75	
56	2.86	2.75	2.70	2.67	2.85	2.69	2.56	2.65	2.80	2.70	2.72	2.54	
60	2.82	2.69	2.66	2.53	2.70	2.64	2.55	2.64	2.74	2.74	2.64	2.56	
61	2.98	2.85	2.73	2.75	2.89	2.81	2.66	2.57	2.91	2.84	2.79	2.70	
62	3.18	3.14	3.04	2.94	3.13	3.05	3.06	2.84	3.21	3.11	2.98	3.01	
63	4.39	4.06	3.92	3.87	4.26	4.09	3.75	3.72	4.32	4.13	4.03	4.09	
64	5.51	5.30	5.19	4.82	5.36	5.10	4.94	4.78	5.49	5.29	5.05	4.89	
65	6.94	6.43	6.27	6.23	6.96	6.37	5.95	5.79	7.34	6.94	6.71	6.61	
66	9.63	8.82	7.40	7.23	9.12	8.41	7.94	7.10	9.20	8.56	8.13	7.88	
67	11.27	10.89	10.66	8.44	10.73	9.72	9.37	8.84	10.79	9.93	9.31	8.98	
68	12.73	11.90	11.09	11.95	12.01	10.86	10.11	9.69	12.16	11.14	10.36	9.87	
69	13.66	13.14	12.81	11.84	12.92	11.78	11.01	10.46	13.18	12.12	11.32	10.74	
70	14.30	13.66	13.39	13.37	13.59	12.32	11.47	10.95	13.98	12.93	12.15	11.58	
71	14.73	13.97	13.60	13.57	14.08	12.72	11.78	11.18	14.59	13.58	12.87	12.37	
72	14.97	14.10	13.63	13.49	14.37	12.96	11.96	11.30	14.97	14.03	13.41	13.02	
73	15.08	14.12	13.54	13.30	14.56	13.12	12.10	11.41	15.26	14.40	13.89	13.65	
74	15.01	13.98	13.33	12.99	14.55	13.12	12.11	11.43	15.31	14.53	14.12	14.00	
75	14.79	13.72	13.01	12.60	14.40	13.01	12.03	11.38	15.20	14.51	14.18	14.17	
76	14.55	13.48	12.77	12.34	14.18	12.83	11.87	11.25	14.99	14.33	14.04	14.05	
77	14.32	13.26	12.54	12.11	13.98	12.65	11.73	11.13	14.79	14.16	13.89	13.86	
78	13.82	12.73	11.96	11.45	13.57	12.33	11.50	10.90	14.40	13.89	13.72	11.15	
79	12.96	11.89	11.11	10.57	12.722	11.55	10.79	10.39	13.66	13.04	12.68	10.63	
80	11.46	9.72	10.00	9.54	11.28	10.37	9.64	9.03	11.92	11.18	11.17	8.43	
81	10.46	9.67	9.13	8.82	10.28	9.36	8.62	8.06	10.67	9.74	10.37	7.63	
82	9.43	8.80	8.29	8.02	9.10	8.30	8.03	7.89	9.54	9.24	8.56	6.90	
83	8.45	7.75	7.30	7.08	8.25	7.64	7.32	6.63	8.66	7.93	7.07	5.93	
84	6.59	6.29	6.04	5.88	6.32	5.77	5.51	5.25	6.32	5.90	5.70	5.93	
85	5.19	5.05	4.78	4.60	5.09	4.74	4.58	4.45	5.10	4.93	4.56	4.58	

Table A5.7 The same as in Table A5.5, but for azimuth angles $\varphi = 225^{\circ}$, 270°, and 315°

Table A5.8 Cutoff rigidities averaged over azimuth angles are given for different zenith angles of incoming particles, together with vertical cutoffs. For the forward part of latitude survey in 1996/97 (According to Dorman et al., 2001)

Days of year	Vertical cutoff (GV)		Average inclin	ed cutoff (GV)
1996/97	$ heta=0^\circ$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$
355	5.15	5.17	5.22	5.37	5.35
356	5.19	5.18	5.24	5.33	5.38
357	6.26	6.24	6.28	6.32	6.52
358	8.61	8.75	8.75	8.86	9.26
359	9.89	10.2	10.67	11.27	11.70
360	11.10	11.18	11.82	12.98	13.94
361	11.82	12.06	12.57	13.93	14.8
362	13.78	13.95	14.66	15.82	17.82
363	14.91	15.17	16.00	17.50	19.89
364	15.58	15.86	16.76	18.4	21.02
365	15.95	16.25	17.17	18.87	21.61
366	16.18	16.48	17.42	19.14	21.92
1	16.43	16.74	17.7	19.45	22.28
2	16.56	16.87	17.83	19.6	22.46
3	16.5	16.81	17.77	19.53	22.37
4	16.26	16.56	17.51	19.23	22.00
5	15.74	16.11	16.93	18.57	21.22
6	14.9	15.26	16.00	17.52	19.8
7	14.06	14.39	15.05	16.36	18.56
8	12.86	13.01	13.57	14.75	15.88
9	11.24	11.42	11.99	12.49	13.48
10	9.18	9.18	9.12	9.09	9.60
11	6.72	6.74	6.75	6.82	7.01
12	5.19	5.29	5.36	5.42	5.42
13	4.00	3.97	3.98	3.98	4.00
14	3.08	3.11	3.12	3.11	3.12
15	2.52	2.52	2.53	2.55	2.55
16	2.08	2.13	2.11	2.12	2.13
17	1.76	1.81	1.79	1.80	1.80
18	1.72	1.69	1.70	1.69	1.70
19	1.73	1.81	1.80	1.79	1.80
20	1.66	1.70	1.70	1.70	1.71
21	1.67	1.69	1.67	1.67	1.69
22	1.7	1.73	1.71	1.73	1.74
23	2.29	2.37	2.4	2.41	2.43
24	2.53	2.59	2.55	2.58	2.61
25	2.53	2.55	2.57	2.58	2.57
26	1.83	1.85	1.85	1.87	1.84
27	0.98	1.01	1.01	1.02	1.02

Table A5.9 Weights of five zenith zones are given together with $R_{cp}^{ap}(\theta,t)$ and $R_{cp}^{ap}(\theta,t) - R_{cp}$. For the forward part of the latitude survey in 1996 (days 355–366) and 1997 (days 1–27) (According to Dorman et al., 2001)

Days			Weights			$R^{ap}_{cp}(\theta,t)$ GV	$R_{cp}^{ap}(\theta,t) - R_{cp}$ GV
	$\theta = 0^{\circ}$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$		
355	0.08149	0.47069	0.364439	0.080634	0.002754	5.203214	0.053214
356	0.081464	0.470594	0.364487	0.080701	0.002761	5.215341	0.025341
357	0.080774	0.468026	0.365764	0.082511	0.002933	6.263668	0.003668
358	0.079259	0.462386	0.36857	0.086485	0.003311	8.750106	0.140106
359	0.078433	0.459314	0.370099	0.088649	0.003517	10.44976	0.55976
360	0.077653	0.45641	0.371543	0.090695	0.003712	11.58507	0.485067
361	0.077188	0.454682	0.372403	0.091913	0.003828	12.41376	0.593761
362	0.075924	0.449978	0.374743	0.095227	0.004144	14.39726	0.617264
363	0.075195	0.447266	0.376093	0.097138	0.004326	15.70934	0.799344
364	0.074763	0.445658	0.376893	0.098271	0.004433	16.45074	0.870743
365	0.074524	0.44477	0.377334	0.098896	0.004493	16.85797	0.90797
366	0.074376	0.444218	0.377609	0.099285	0.00453	17.10137	0.921371
1	0.074215	0.443618	0.377907	0.099708	0.00457	17.3753	0.945301
2	0.074131	0.443306	0.378063	0.099928	0.004591	17.50842	0.948416
3	0.07417	0.44345	0.377991	0.099827	0.004582	17.44687	0.946868
4	0.074324	0.444026	0.377704	0.099421	0.004543	17.18668	0.926677
5	0.07466	0.445274	0.377084	0.098541	0.004459	16.65677	0.916773
6	0.075202	0.44729	0.376081	0.097121	0.004324	15.75034	0.850343
7	0.075743	0.449306	0.375078	0.0957	0.004189	14.81855	0.758546
8	0.076517	0.452186	0.373645	0.093671	0.003995	13.38221	0.522213
9	0.077562	0.456074	0.371711	0.090932	0.003735	11.7229	0.4829
10	0.078891	0.461018	0.369251	0.087448	0.003403	9.151404	-0.0286
11	0.080478	0.466922	0.366314	0.083289	0.003007	6.749528	0.029528
12	0.081464	0.470594	0.364487	0.080701	0.002761	5.318217	0.128217
13	0.082232	0.47345	0.363066	0.078689	0.002569	3.976962	-0.02304
14	0.082825	0.475658	0.361968	0.077133	0.002421	3.111159	0.031159
15	0.083187	0.477002	0.361299	0.076186	0.002331	2.525968	0.005968
16	0.08347	0.478058	0.360774	0.075442	0.00226	2.117857	0.037857
17	0.083677	0.478826	0.360391	0.074901	0.002208	1.797837	0.037837
18	0.083703	0.478922	0.360344	0.074834	0.002202	1.696137	-0.02386
19	0.083696	0.478898	0.360356	0.07485	0.002204	1.798182	0.068182
20	0.083741	0.479066	0.360272	0.074732	0.002192	1.696672	0.036672
21	0.083735	0.479042	0.360284	0.074749	0.002194	1.679625	0.009625
22	0.083716	0.47897	0.36032	0.0748	0.002199	1.720304	0.020304
23	0.083335	0.477554	0.361024	0.075797	0.002294	2.377333	0.087333
24	0.08318	0.476978	0.361311	0.076203	0.002332	2.569841	0.039841
25	0.08318	0.476978	0.361311	0.076203	0.002332	2.557895	0.027895
26	0.083632	0.478658	0.360475	0.07502	0.00222	1.849806	0.019806
27	0.08418	0.480698	0.35946	0.073582	0.002083	1.008231	0.028231

Table A5.10 Cutoff rigidities averaged over eight azimuth angles are given for different zenith angles of incoming particles, together with vertical cutoffs for the backward part of the latitude survey in 1996/97

No.	Day of 1997	Latitude	Longitude	itudeEight azimuth average cutoff rigidity (GV)				
				$\theta = 0^{\circ}$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$
59	48	-57.565	170.462	0.40	0.40	0.39	0.39	0.40
60	49	-52.037	170.453	0.94	0.94	0.93	0.94	0.93
61	50	-46.451	171.694	1.86	1.88	1.91	1.91	1.89
62	51	-43.607	172.751	2.55	2.58	2.56	2.58	2.58
63	52	-43.607	172.723	2.56	2.56	2.57	2.57	2.60
64	53	-42.904	173.329	2.83	2.79	2.77	2.78	2.77
65	54	-40.298	171.086	3.36	3.37	3.40	3.37	3.43
66	55	-39.919	163.772	3.09	3.10	3.13	3.14	3.20
67	56	-39.584	157.170	2.95	2.93	2.91	2.92	2.88
71	60	-36.924	129.369	2.86	2.85	2.84	2.83	2.82
72	61	-36.137	123.245	2.93	3.02	3.03	3.00	2.98
73	62	-34.861	116.206	3.35	3.32	3.35	3.37	3.37
74	63	-31.632	110.474	4.50	4.55	4.47	4.44	4.41
75	64	-28.092	105.127	5.75	5.76	5.83	5.91	5.98
76	65	-24.472	99.935	7.57	7.55	7.45	7.48	7.63
77	66	-20.922	95.022	10.12	10.28	10.51	10.75	10.80
78	67	-17.358	90.285	12.12	12.51	12.80	13.84	14.60
79	68	-13.805	85.611	13.52	13.74	14.38	15.56	17.64
80	69	-10.133	80.926	14.60	15.18	15.66	17.11	19.29
81	70	-6.557	76.324	15.41	15.53	16.56	18.15	20.69
82	71	-3.051	71.732	15.99	16.28	17.20	18.88	21.58
83	72	0.301	66.867	16.33	16.63	17.58	19.31	22.11
84	73	4.256	62.045	16.55	16.86	17.82	19.59	22.44
85	74	7.656	57.482	16.53	16.84	17.80	19.56	22.42
86	75	10.992	52.902	16.34	16.64	17.59	19.33	22.15
87	76	12.439	47.758	16.09	16.39	17.32	19.03	21.80
88	77	13.844	42.947	15.85	16.14	17.06	18.74	21.45
89	78	18.252	40.105	15.34	15.61	16.49	18.09	20.63
90	79	23.111	37.100	14.42	14.67	15.43	16.84	18.92
91	80	28.076	33.680	12.72	13.05	13.58	14.89	16.05
92	71	30.812	32.253	11.48	11.63	12.36	13.55	14.35
93	82	33.270	28.403	10.19	10.34	11.20	11.48	12.21
94	83	36.094	22.574	9.23	9.32	9.48	9.62	10.12
95	84	40.463	18.202	6.87	6.87	6.86	6.90	7.01
96	85	43.666	13.806	5.44	5.46	5.50	5.52	5.63

No.		We	eight coefficie	ents		$R^{ap}_{cp}(\theta,t)$	R_{eff}	$R_{cp}^{ap}(\theta,t) - R_{cp}$
	$\theta = 0^{\circ}$	$\theta = 15^{\circ}$	$\theta = 30^{\circ}$	$\theta = 45^{\circ}$	$\theta = 60^{\circ}$		-	
59	0.084554	0.482090	0.358768	0.072601	0.001989	0.393847	0.40	-0.006153
60	0.084206	0.480794	0.359412	0.073515	0.002076	0.937013	0.94	-0.002987
61	0.083612	0.478586	0.360511	0.075070	0.002224	1.890848	1.86	0.030848
62	0.083167	0.476930	0.361335	0.076237	0.002336	2.569445	2.55	0.019445
63	0.083161	0.476906	0.361347	0.076254	0.002337	2.560551	2.56	0.000551
64	0.082987	0.476258	0.361669	0.076711	0.002381	2.785442	2.83	-0.044558
65	0.082645	0.474986	0.362302	0.077607	0.002466	3.376990	3.36	0.016990
66	0.082819	0.475634	0.361979	0.077150	0.002422	3.111778	3.09	0.021778
67	0.082909	0.475970	0.361812	0.076913	0.002400	2.924075	2.95	-0.025925
71	0.082967	0.476186	0.361705	0.076761	0.002385	2.841693	2.86	-0.018307
72	0.082922	0.476018	0.361788	0.076880	0.002397	3.015603	2.93	0.085603
73	0.082651	0.475010	0.362290	0.077590	0.002464	3.334185	3.35	-0.015815
74	0.081910	0.472250	0.363663	0.079535	0.002650	4.504501	4.50	0.004501
75	0.081103	0.469250	0.365156	0.081648	0.002851	5.796496	5.75	0.046496
76	0.079929	0.464882	0.367329	0.084726	0.003144	7.505671	7.57	-0.064329
77	0.078285	0.458762	0.370373	0.089038	0.003554	10.397190	10.12	0.277190
78	0.076995	0.453962	0.372761	0.092420	0.003876	12.718604	12.12	0.598604
79	0.076092	0.450602	0.374433	0.094787	0.004102	14.151170	13.52	0.631170
80	0.075395	0.448010	0.375722	0.096614	0.004276	15.519026	14.60	0.919026
81	0.074873	0.446066	0.376690	0.097983	0.004406	16.187367	15.41	0.777367
82	0.074498	0.444674	0.377382	0.098964	0.004499	16.884820	15.99	0.894820
83	0.074279	0.443858	0.377788	0.099539	0.004554	17.260201	16.33	0.930201
84	0.074137	0.443330	0.378051	0.099911	0.004590	17.495431	16.55	0.945431
85	0.074150	0.443378	0.378027	0.099877	0.004586	17.475157	16.53	0.945157
86	0.074273	0.443834	0.377800	0.099556	0.004556	17.272599	16.34	0.932599
87	0.074434	0.444434	0.377501	0.099133	0.004515	17.005376	16.09	0.915376
88	0.074589	0.445010	0.377215	0.098727	0.004477	16.745810	15.85	0.895810
89	0.074918	0.446234	0.376606	0.097865	0.004395	16.188473	15.34	0.848473
90	0.075511	0.448442	0.375507	0.096309	0.004247	15.160246	14.42	0.740246
91	0.076608	0.452522	0.373478	0.093435	0.003973	13.405793	12.72	0.685793
92	0.077407	0.455498	0.371997	0.091338	0.003773	12.077352	11.48	0.597352
93	0.078239	0.458594	0.370457	0.089156	0.003566	10.756458	10.19	0.566458
94	0.078859	0.460898	0.369311	0.087533	0.003411	9.401215	9.23	0.171215
95	0.080381	0.466562	0.366493	0.083542	0.003031	6.868538	6.87	-0.001462
96	0.081303	0.469994	0.364785	0.081124	0.002801	5.475422	5.44	0.035422

Table A5.11 Weights of five zenith zones with $R_{cp}^{ap}(\theta,t)$ and $R_{cp}^{ap}(\theta,t) - R_{cp}$. For the backward part of the latitude survey in 1996–1997 (From Dorman et al., 2003)

Appendix to Chapter 6



Fig. A6.1 Planetary contours of trajectory-derived averaged global magnetic cutoff rigidities determined by Eq. 6.4 for the geocentric dipole field model with dipole moments 11.7×10^{25} Gs.cm³ (*top* panel, 2,000 years ago) and 7.8 × 10²⁵ Gs.cm³ (*bottom* panel, present time) at $\theta_{max} = 85^{\circ}$ (According to Flückiger et al., 2003)



Fig. A6.2 The same as in Fig. A6.1, but for the eccentric dipole field model with dipole moment 11.7×10^{25} Gs.cm³ (*top* panel, 2,000 years ago) and 7.8×10^{25} Gs.cm³ (*bottom* panel, present time) at $\theta_{\text{max}} = 85^{\circ}$ (According to Flückiger et al., 2003)



Fig. A6.3 Contour lines for global cutoff rigidity 2 GV in the northern (*left*) and southern (*right*) hemispheres for geomagnetic dipole moment 7.8×10^{25} Gs.cm³. The solid red lines refer to a geocentric magnetic dipole, whereas the dashed blue lines refer to an eccentric dipole (According to Flückiger et al., 2003)

Station	Störmer	Dipole	Undisturb.	5.0; 0.5	5.0; 1.0	6.25; 0.5	6.25; 1.0	6.5; 0.5	7.5; 1.0
Amsterdam	1.763	1.769	2.313	1.451	1.107	1.490	1.079	1.848	1.497
Awarua	2.181	2.183	1.850	1.189	0.896	1.151	0.878	1.324	0.963
Bergen	0.776	0.779	0.946	0.627	0.462	0.616	0.458	0.594	0.452
Bismark	1.414	1.403	1.272	0.834	0.622	0.812	0.613	0.788	0.602
Bologna	3.651	3.663	4.225	3.204	2.327	3.743	3.344	3.965	3.656
Bristol	1.657	1.660	2.313	1.447	1.104	1.483	1.076	1.842	1.490
Budapest	3.312	3.326	3.670	2.548	1.730	3.172	2.769	3.455	3.119
Cape Schmidt	0.669	0.671	0.589	0.393	0.291	0.390	0.290	0.383	0.288
Chicago	2.000	1.984	1.777	1.144	0.861	1.107	0.843	1.239	0.871
Christchurch	2.964	2.969	2.630	1.622	1.230	1.814	1.279	2.247	1.914
Churchill	0.253	0.253	0.199	0.136	0.098	0.136	0.098	0.136	0.098
Climax	2.934	2.915	2.849	1.767	1.349	2.110	1.607	2.499	2.151
College	0.508	0.507	0.497	0.334	0.249	0.332	0.248	0.328	0.247
Columbia	2.661	2.643	2.456	1.535	1.164	1.649	1.140	2.043	1.702
Davis Strait	0.025	0.025	0.033	0.023	0.017	0.023	0.017	0.023	0.017
Deep River	1.226	1.216	1.066	0.703	0.522	0.689	0.517	0.664	0.509
Dunedin	2.387	2.389	2.048	1.303	0.987	1.254	0.964	1.545	1.200
Ellsworth	0.362	0.367	0.685	0.456	0.340	0.452	0.338	0.440	0.335
Fredericksburg	2.601	2.584	2.347	1.465	1.109	1.523	1.082	1.913	1.563
Freiburg	2.697	2.705	3.411	2.140	1.593	2.714	2.257	3.128	2.698
Frobisher	0.060	0.059	0.057	0.038	0.028	0.038	0.028	0.038	0.028
Godhavn	0.013	0.014	0.022	0.015	0.011	0.015	0.011	0.015	0.011
Gottingen	2.090	2.099	2.639	1.630	1.236	1.804	1.308	2.302	1.924

Table A6.1 Changes in vertical threshold rigidity (in GV) caused by the presence of a thin equatorial ring current (According to Sauer, 1963)

(Continued)

Station	Störmer	Dipole	Undisturb.	5.0; 0.5	5.0; 1.0	6.25; 0.5	6.25; 1.0	6.5; 0.5	7.5; 1.0
Hafelekar	2.992	3.004	3.532	2.262	1.654	2.992	2.575	3.310	2.956
Halle	2.175	2.185	2.693	1.668	1.268	1.870	1.375	2.385	1.988
Hamburg	1.738	1.745	2.137	1.367	1.031	1.333	1.006	1.672	1.337
Harwell	1.680	1.684	2.326	1.455	1.110	1.496	1.082	1.854	1.508
Heiss Island	0.171	0.176	0.105	0.071	0.052	0.071	0.052	0.071	0.052
Herstmonceux	1.849	1.854	2.543	1.558	1.179	1.698	1.169	2.149	1.819
Hobart	2.179	2.173	1.831	1.177	0.887	1.136	0.868	1.295	0.930
Iowa City			1.880	1.164	0.889	1.205	0.909	1.356	0.996
Kinina	0.459	0.462	0.461	0.307	0.230	0.306	0.229	0.303	0.228
Kuklungsborn	1.726	1.733	2.068	1.329	1.002	1.276	0.979	1.586	1.245
Leeds	1.346	1.349	1.801	1.158	0.872	1.125	0.854	1.270	0.903
Legionowo	2.355	2.368	2.651	1.645	1.251	2.120	1.340	2.302	1.942
Lincoln	2.362	2.342	2.178	1.382	1.047	1.366	1:021	1.707	1.365
Lomnicky Stit	2.987	3.002	3.341	2.084	1.575	2.756	2.215	3.049	2.739
London	1.727	1.732	2.375	1.482	1.134	1.558	1.108	1.903	1.580
Loparskaya	0.577	0.582	0.503	0.337	0.251	0.335	0.250	0.331	0.249
MacQuirie Isl.	0.805	0.805	0.600	0.400	0.296	0.397	0.295	0.390	0.293
M.I.T.	1.944	1.931	1.754	1.127	0.847	1.090	0.830	1.208	0.845
Mawson	0.106	0.106	0.202	0.138	0.099	0.138	0.099	0.137	0.099
Melbourne	3.166	3.158	2.826	1.742	1.323	2.037	1.538	2.455	2.133
Minneapolis	1.556	1.544	1.378	0.901	0.673	0.875	0.662	0.849	0.649
Mirny	0.036	0.036	0.041	0.028	0.020	0.028	0.020	0.028	0.020
Moscow	2.386	2.403	2.218	1.414	1.073	1.426	1.047	1.768	1.430
Munich	2.811	2.821	3.425	2.170	1.606	2.759	2.287	3.159	2.740
Murchison Bay	0.066	0.067	0.053	0.036	0.026	0.036	0.026	0.036	0.026
Murmansk	0.550	0.554	0.481	0.320	0.239	0.318	0.238	0.315	0.237
Ottawa	1.313	1.303	1.152	0.758	0.563	0.740	0.557	0.715	0.547
Pic du Midi	3.465	3.471	4.357	3.006	2.240	3.633	3.154	3.903	3.536
Port-Francais	1.250	1.241	1.224	0.803	0.597	0.782	0.589	0.757	0.579
Prague	2.548	2.557	2.943	1.820	1.395	2.229	1.712	2.657	2.256
Prince Albert	0.742	0.737	0.649	0.435	0.321	0.431	0.319	0.422	0.317
Resolute	0.003	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Saskatoon	0.869	0.862	0.771	0.513	0.382	0.506	0.379	0.489	0.376
Stockholm	1.179	1.185	1.280	0.842	0.628	0.820	0.619	0.796	0.608
Sulphur Mt	1 1 56	1 148	1.084	0.715	0.531	0.699	0.525	0.675	0.517
Sverdlovsk	2.907	2.928	2.254	1 413	1.075	1.424	1.048	1.818	1 479
Swarthmore	2.207	2.920	1 998	1 273	0.961	1 227	0.939	1 488	1 1 3 4
Svowa Base	0.219	0.220	0.419	0.280	0.204	0.279	0.204	0.277	0.203
Thule	0.000	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Tixie Bay	0.908	0.002	0.585	0.393	0.290	0.390	0.289	0.383	0.287
Tromso	0.345	0.349	0.346	0.234	0.174	0.233	0.173	0.232	0.173
Uppeala	1 1 1 5	1 1 2 1	1 208	0.204	0.594	0.255	0.587	0.252	0.175
Washington	2 447	2 4 2 7	2 182	1 382	1.046	1 366	1.021	1 709	1 365
Washington Mt	1.465	1 455	1 314	0.850	0.640	0.836	0.631	0.811	0.610
Weissenau	2 801	2 810	3 501	2 228	1 630	2 848	2 342	3 242	2 822
Wellington	3 503	3 506	3 10/	1 06/	1 503	2.540	2.054	2 010	2.522
Wilkes	0.028	0.028	0.015	0.010	0.007	0.010	0.007	0.010	0.007
Vakutek	2 277	2 302	1 705	1 100	0.007	1.064	0.007	1 154	0.007
Zugsnitze	2.577	2.552	3 495	2 222	1 634	2 935	2 517	3 266	2 905
- Soprize	2.751	2.705	5.175		1.05 T	2.755	2.017	5.200	2.705

Table A6.1 (Continued)

Table A6.2	Impact zo	ones on the	earth of p	particles	incident	vertically,	a ring	current	being p	resent
(According	to Ray, 19	956b)								

Rigidity, GV	r_c/r_E	M_c/M_E	Latitude of source	Latitude of impact	Longitude of shift
2	7.5	1	64.6	80	17
			34.9	70	20
			16.4	65	25
			3.7	62	31.6
			-5.3	60	39.3
			-9.9	59	46.3
			-13.7	58	53.1
			-16.2	57	60.2
			-17.3	56	70.8
			-16.9	55.5	77.4
2	7.5	0.5	60.0	80	18
			26.0	70	26
			6.6	65	34
			-5.7	62	44
			-13.2	60	54.7
			-16.0	59	62.1
			-18.0	58	71.1
			-17.7	57	83.0
			-17.4	56	95.6
			-17.5	55.5	104.5
2	5	0.5	61.8	80	25
			31.9	70	30
			15.5	65	36
			4.9	62	42.2
			-1.6	60	49.4
			-5.9	59	53.6
			-9.3	58	59.0
			-12.0	57	64.9
			-13.7	56	73.7
			-14.1	55.5	78.6
6	7.5	1	53.1	75	18
			12.5	60	30
			-1.4	55	39
			-13.5	50	55.1
			-16.9	44	92.6
			-15.6	42	110.4
			-12.7	41	122.2
			-6.6	40	136.5
6	5	0.5	54	75	20
			14.2	60	32
			0.5	55	40
			-11.7	50	54.9
			-16.8	44	89.2
			-15.8	42	106.2
			-14.6	41	116.9
			-10.6	40	128.4

(Continued)

Rigidity, GV	r_c/r_E	M_c/M_E	Latitude of source	Latitude of impact	Longitude of shift
10	5	0.5	46.4	70	19
			7.8	55	30
			-6.2	50	40
			-18.6	45	56.4
			-23.5	40	84.3
			-22.1	36	115.7
			-7.1	33	144.9
			11.6	31.5	174.8
			-9.7	30	218.8

Table A6.2 (Continued)

Table A6.3 Asymptotic directions for geomagnetic latitudes 50° and 60° if the magnetic field is confined to a cavity with radius r_m (According to Asaulenko et al., 1965)

Latitude λ	R , GV	Angles	Dipole	$r_m = 12r_E$	$r_m = 10r_E$	$r_m = 8r_E$
50°	3.5	Ψ	136.5	160.1	178.9	_
		Λ	-3.6	3.5	9.8	_
	4.2	Ψ	107.7	121.3	128.6	146.7
		Λ	-15.3	-13.3	-11.6	-5.8
	5.38	Ψ	83.1	91.4	95.5	104.2
		Λ	-21.5	-21.9	-22.2	-22.6
	7.32	Ψ	57.0	61.9	64.1	68.0
		Λ	-10.5	-11.2	-11.7	-12.7
	10.0	Ψ	48.1	51.5	52.9	55.6
		Λ	-9.2	-9.6	-10.0	-10.7
60°	1.88	Ψ	84.5	115.5	136.9	_
		Λ	-21.1	-20.8	-17.7	_
	2.63	Ψ	60.5	75.0	81.8	97.4
		Λ	-13.5	-16.5	-18.5	-22.7
	3.72	Ψ	48.5	57.1	60.9	67.2
		Λ	-3.7	-5.9	7.3	-10.4
	3.74	Ψ	41.1	46.5	48.4	52.0
		Λ	5.6	4.4	4.0	1.9
	10.5	Ψ	30.9	33.9	35.2	36.8
		Λ	18.5	18.0	17.6	17.0

$\overline{R(\mathrm{GV})}$	Angles		Latitude $\lambda =$	60°	Latitude $\lambda = 60^{\circ}$		
		Dipole	$r_c = 5r_E$	$r_c = 5r_E$	Dipole	$r_c = 5r_E$	$r_c = 5r_E$
			$r_m = 8r_E$	$r_m = 12r_E$		$r_m = 8r_E$	$r_m = 12r_E$
1.88	Ψ	84.5	_	72.3	_	_	_
	Λ	-21.1	_	-1.5	-	_	_
2.20	Ψ	70.8	89.2	59.2	-	_	_
	Λ	-18.7	-12.7	5.6	-	_	_
2.63	Ψ	60.5	71.3	51.2	-	_	_
	Λ	-13.5	-5.5	9.3	-	_	_
3.15	Ψ	53.3	59.9	42.5	193.7	_	101.6
	Λ	-11.0	-2.9	10.8	17.1	_	-13.7
3.72	Ψ	48.5	53.9	39.8	12.5	114.1	79.8
	Λ	-3.7	4.1	14.1	-9.4	-13.8	-14.6
4.37	Ψ	42.7	45.9	34.1	104.7	96.7	70.4
	Λ	0.3	7.8	16.1	-17.5	-18.1	-17.2
5.74	Ψ	41.1	42.6	32.6	75.9	71.3	56.4
	Λ	5.6	11.1	16.7	-19.2	-15.2	-11.1
7.73	Ψ	34.8	35.2	28.7	54.4	52.2	42.5
	Λ	16.7	20.6	24.2	-9.9	6.3	-3.2
10.5	Ψ	30.9	30.2	24.6	47.5	45.6	38.8
	Λ	18.5	21.3	23.8	-8.7	-6.0	-3.9
14.9	Ψ	33.7	32.9	28.4	45.4	44.1	39.1
	Λ	23.3	24.9	26.3	1.0	12.6	4.0

 Table A6.4 Combined effect of a ring current and of the finite dimension of the magnetosphere on the asymptotic directions (According to Asaulenko et al., 1965)

Appendix to Chapter 7

Parameter	K _p	K_p	K _p	K _p	K_p	$K_p \ge 5^-$
	$= 0, 0^+$	$=1^{-}, 1, 1^{+}$	$=2^{-}, 2, 2^{+}$	$=3^{-}, 3, 3^{+}$	$=4^{-}, 4, 4^{+}$	-
N	3975	9977	9848	7309	3723	1850
$\langle B_e \rangle$	15.49	19.06	21.71	25.48	28.58	32.88
σ	6.51	8.52	9.75	11.35	12.41	15.12
C_1	98.72	35.64	77.45	70.12	$\sim \! 162.5$	$\sim \! 128.4$
C_2	10014	12800	14588	16125	$\sim \! 15806$	$\sim \! 16184$
C_3	15.03	14.37	64.85	90.71	160.6	149.1
C_4	76.62	124.5	123.9	38.08	5.888	215.5
C_5	10237	13543	16229	19630	~ 27534	~ 36435
C_6	1.813	2.316	2.641	3.181	3.607	4.090
C_7	31.10	35.64	42.46	47.50	51.10	49.09
$c_8 \times 10$	$\sim \! 0.7464$	0.741	0.7611	1.327	$\sim \! 1.006$	~ 0.231
$c_9 imes 10$	0.7764	1.081	1.579	1.864	~ 1.927	~ 1.359
$c_{10} \times 10^2$	0.3303	0.3924	0.4078	1.382	3.353	1.989
C_{11}	1.129	1.451	1.391	1.488	~ 1.392	~ 2.298
$c_{12} \times 10^{2}$	0.1663	0.202	0.153	0.2962	0.1594	0.4911
$c_{13} \times 10^2$	0.0988	0.111	0.0727	0.0897	0.2439	0.3421
C_{14}	18.21	21.37	21.86	22.74	22.41	21.79
$c_{15} \times 10^2$	3.018	4.567	4.199	4.095	~ 4.925	~ 5.447
$c_{16} \times 10^2$	3.829	5.382	6.523	9.223	~ 11.53	~ 11.49
$c_{17} \times 10$	1.283	1.457	6.412	10.59	$\sim \! 13.99$	~ 22.14
$c_{18} \times 10^{3}$	1.973	2.742	0.948	1.766	~ 0.716	$\sim \! 13.55$
$c_{19} \times 10^{3}$	0.717	1.244	2.276	3.034	2.696	1.185
Δx	24.74	22.33	20.90	18.64	18.31	19.48
a_{RC}	8.161	8.119	6.283	6.266	6.196	5.831
D_o	2.08	1.664	1.541	0.9351	0.7677	0.3325
YRC	0.8799	0.9324	4.183	5.389	5.072	6.472
r_c	9.084	9.238	9.609	8.573	10.06	10.47
G	3.838	2.426	6.591	5.935	6.668	9.081
a_T	13.55	13.81	15.08	15.63	16.11	15.85
D_y	26.94	28.83	30.57	31.47	30.04	25.27
<i>x</i> ₀	5.745	6.052	7.435	8.103	8.260	7.976

Table A7.1 Values of parameters in dependence of K_p (From Tsyganenko, 1989)



Fig. A7.1 Distribution on the magnetopause of the normal component of the unshielded field of the equatorial current sheet with the *o*-type symmetry in Eq. 7.35 (n = 3 and m = 4; *left* panel), to be compared with the corresponding distribution of the best fit shielding field, approximated using the scalar potential Eq. 7.41 (*right*) (From Tsyganenko and Sitnov, 2007)



Fig. A7.2 Color-coded distribution of B_z component of the external model field (without earth's contribution) in the equatorial plane, for four intervals of Kp index: Kp = 0 (*top left*), Kp = 2 (*top right*), Kp = 4 (*bottom left*), and Kp from 6 to 7+ (*bottom right*) (From Tsyganenko and Sitnov, 2007)



Fig. A7.3 Same as in Fig. A7.2, but for four intervals of IMF B_z : $B_z > +8nT$ (*top left*), $3nT \le B_z < 5nT$ (*top right*), $-5nT \le B_z < -3nT$ (*bottom left*), and $B_z < -8nT$ (*bottom right*) (From Tsyganenko and Sitnov, 2007)



Fig. A7.4 Same as in Fig. A7.3, but for the main (*left*) and recovery (*right*) phases of a moderate storm (From Tsyganenko and Sitnov, 2007)



Fig. A7.5 Distributions of the model electric current $\mathbf{j} \sim \nabla \times \mathbf{B}$ in the equatorial plane for the main (*left*) and recovery (*right*) phases of a moderate storm. At the main phase, note a dramatic increase of \mathbf{j} on the nightside, fed by the inflowing/outflowing field-aligned currents in the morning/evening MLT sectors (manifested by diverging/converging \mathbf{j} vectors). At the recovery phase, note a virtually axisymmetric and weaker ring current, gradually merging into the tail current sheet (From Tsyganenko and Sitnov, 2007)



Fig. A7.6 Distribution of Region 1 and 2 FAC (in nA/m^2) at the ionospheric level, corresponding to the strong southward IMF data subset (see Fig. A7.3, *bottom right* panel). Positive (blue) and negative (red) values correspond to inflowing and outflowing current, respectively (From Tsyganenko and Sitnov, 2007)



Fig. A7.7 Illustrating the tilt angle and twisting effects in the cross-section of the model magnetotail at $x_{\text{GSM}} = -25 r_{\text{E}}$. (*left*) Strongly positive IMF B_z without twisting and (*right*) strongly negative IMF B_z with a twist angle 30°, corresponding to a strong and positive IMF B_y . Note a much larger warping of the current sheet in the former case (From Tsyganenko and Sitnov, 2007)



Fig. A7.8 Solar wind conditions for the 25–26 September 1998 storm event. The top and middle panels show solar wind number density, velocity, and ram pressure, and IMF components in GSM coordinates, measured by the Wind satellite at 180 $r_{\rm E}$ upstream. The bottom panel shows the *Dst* index (From Huang et al., 2006)



Fig. A7.9 Magnetic field comparisons of data and models during the September 25–26, 1998 storm event. The black lines are the measurements from GOES 8. The red and green lines are the predicted values of the T03 model and the MHD code at the GOES 8 positions using time-dependent solar wind inputs. The dark circles denote when the GOES 8 satellite is at local midnight. The *top* three panels are the vector components of the magnetic fields in dipole coordinates. The *bottom* two panels show the magnetic field magnitude and elevation angle (From Huang et al., 2006)



Fig. A7.10 The same comparison as Fig. A7.9 using GOES 10 data (From Huang et al., 2006)





Fig. A7.11 Three-dimensional magnetic field configurations of the T03 model and the MHD simulations, viewed from dawn at an angle above the equator, before storm (*top*) and during the main phase (*bottom*). The field lines are traced from points on a 6.6 $r_{\rm E}$ -radius circle on the GSM equatorial plane, and at eight equispaced local times. The tick marks on the axes are 10 $r_{\rm E}$ apart and the sun is toward the right of both panels (From Huang et al., 2006)



Fig. A7.12 Current systems maps (panels **a** and **b**) and plasma pressure gradient maps (panels **c** and **d**) calculated from the T03 model and the MHD simulations at the equatorial plane during storm main phase, with a $1.5 \times 1.5 r_E$ data smoothing. The white dashed lines denote the location of geosynchronous orbit (From Huang et al., 2006)



Fig. A7.13 Detail variations of the NM counting rate during 3 h 6–8 of January 20, 2005 at Jungfraujoch in comparison with high-latitude NM on stations Terre Adelie, South Pole, Inuvik, and Barentsburg (From Flückiger et al., 2006)



Fig. A7.14 Calculated planetary distribution of expected CR cutoff rigidities for the moment of the GLE starting (06:56 UT at January 20, 2005) (From Flückiger et al., 2006)

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