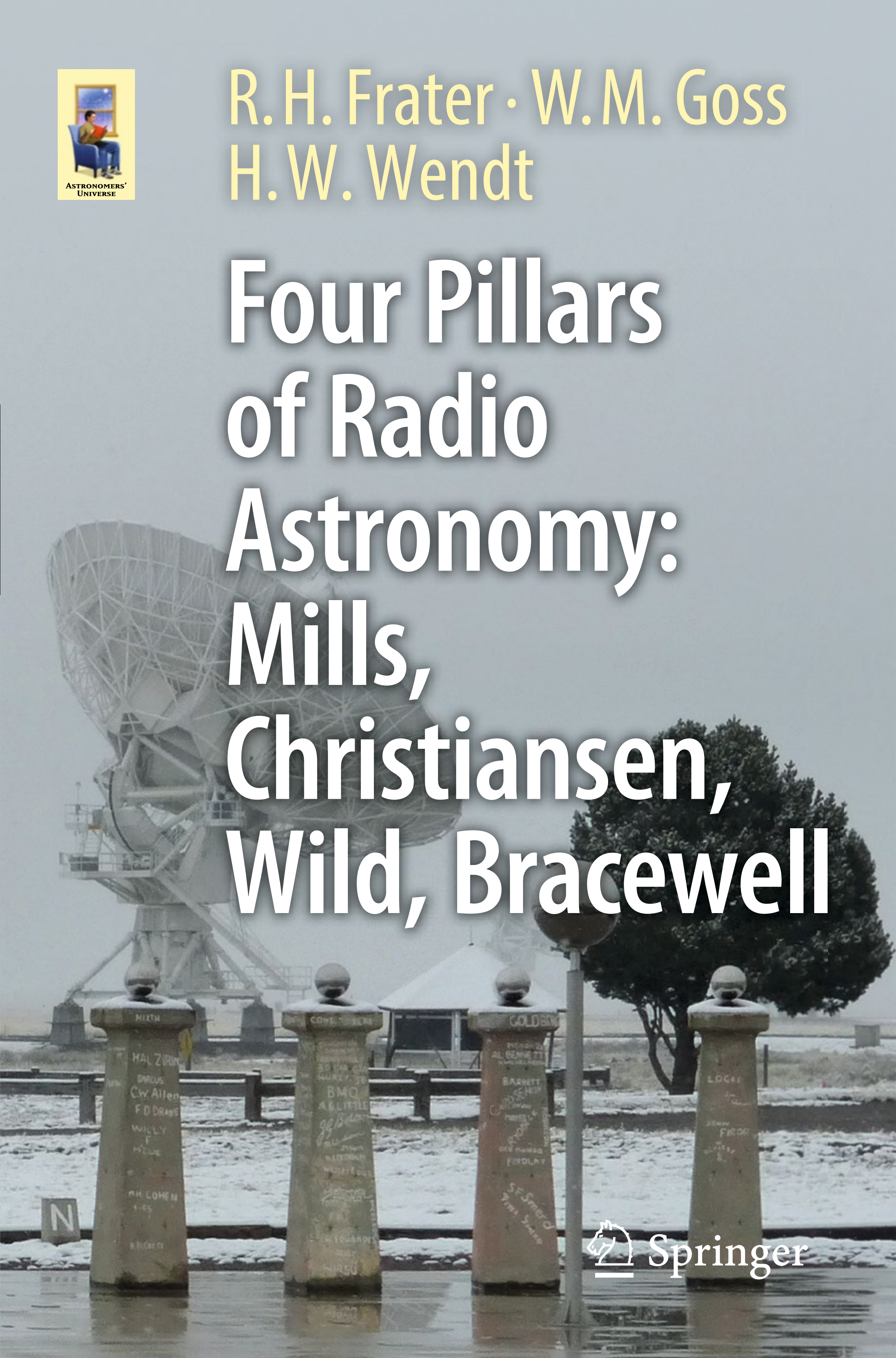

Astronomers' Universe

R. H. Frater · W. M. Goss
H. W. Wendt

Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell

Springer

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Cover image: Four piers (or pillars) in the Bracewell Radio Sundial at the Karl G. Jansky Very Large Array in New Mexico, USA. Photo courtesy of W.M. Goss. 1 April 2017. For more information, see page xv

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Bob Frater: To my wife, Margaret

Miller Goss: For Martin Y. Smith – who made my research on the history of Australian radio astronomy possible

Harry Wendt: For Susan and Tom

Foreword

As one of the beneficiaries of the contributions of these four scientists, it is a privilege to provide the foreword to this book. As a student at the University of Adelaide in the early 1960s, I attended a lecture by Bernie Mills, my introduction to radio astronomy. Later, as a summer student at CSIRO, I learned about radio telescope arrays from Chris Christiansen. *Radiotelescopes* by Christiansen and Högbom and *The Fourier Transform and Its Applications* by Bracewell strongly influenced my career. I visited Ron Bracewell at Stanford in 1968 and added my signature to the telescope pier now illustrated on the front cover of this book. The Australia Telescope Compact Array (ATCA) grew from the tradition of innovative radio astronomy instrumentation discussed in this book. I became its first director. The proposal to make ATCA part of a National Facility was led by Paul Wild, while chairman of CSIRO. One of the authors, Bob Frater, recruited me from the National Radio Astronomy Observatory in the USA as part of a team to develop and operate this new facility.

The authors felt the influences as well. Miller Goss is the world expert on Joe Pawsey and his role in the history of radio astronomy in Australia as mentor to the *Four Pillars*. Bob Frater took up the mantle of the *Pillars* by rejuvenating Australian Radio Astronomy in the 1980s. Harry Wendt is a professional historian who wrote his thesis on the instruments built by the *Four Pillars* and their observatory sites.

This book is not just a collection of stories about four very successful radio astronomers but of the connections between these scientists and a culture which resulted in a profound global influence in the field of imaging radio astronomy. By pulling the careers of these four scientists together, the authors have given us a wonderful cross section of the development of radio astronomy as an exciting new research area. It was a remarkable period in the history of Australian science, when radar research at the end of World War II resulted in an unusual concentration of scientific talent in this isolated country. This was a crucial period in the history of Australia radio astronomy when the competition for resources caused the radio astronomy community, initially concentrated in CSIRO, to split. The *Four Pillars* each went in different directions: Bracewell to Stanford in California, Mills to the University of Sydney physics and Christiansen to University of Sydney engineering; only Wild stayed at CSIRO, eventually becoming the chairman of the organisation.

Each of the *Four Pillars* was involved in the invention of new instruments and algorithms to further the development of imaging in radio astronomy. Mills invented the Mills Cross, Christiansen the Chris Cross and Wild the solar heliograph, and Bracewell provided the mathematical basis for indirect imaging. This snapshot in the development of radio astronomy imaging illustrates the complex interplay between the design of antenna arrays and the formation of images. They each took a different path to solve this problem. Chris made the first earth rotation aperture synthesis image, but to do so he had to use laborious hand calculations of the Fourier transforms. Mills used analogue beam formation with an ingenious array design – the famous "Mills Cross". This avoided the need to calculate Fourier transforms but, in time, it was the digital computers that dominated the field. Mills eventually modified his cross to take advantage of this new technology. Wild successfully played the middle ground and cleverly exploited analogue computers to generate time-varying two-dimensional images of the radio sun – a feat which was only matched by modern aperture synthesis methods in the last decade. Bracewell made a career from the development of mathematical models and algorithms and played a key role in the introduction of Fourier methods based on radio astronomy imaging to the medical imaging field. To quote Bracewell from the end of Chap. 7: "Starting from modest beginnings and by small steps, radio astronomers took the separate field of antennas, receivers and information theory and welded them into image forming systems that have improved by seven orders of magnitude in resolution, surpassing the optical telescope, and inspired other developments in fields as diverse as optics, acoustics, seismic probing and X-ray tomography".

The science the *Four Pillars* covered is remarkably diverse. Mills was involved in both galactic and extragalactic astronomy and in cosmology. Paul Wild made the definitive observations of solar radio activity as well as contributions to ionospheric research, the theory of the atomic transitions of hydrogen and the measurement of magnetic fields in the interstellar medium. Christiansen confirmed the predicted brightening of the limb of the sun. Bracewell's key contributions were the mathematical principles involved in indirect imaging and hence in image deconvolution theory.

The story of Wi-Fi and 802.11 is covered in detail in Chap. 7. The complex history of this development is a key part of this book and illustrates the many complicating factors involved in the creation of a new technology. Many of Chris's students played key roles in the 802.11 wireless development including O'Sullivan, Daniels, Percival and Skellern. One author, Bob Frater, also played a part, and he has contributed to this unique in-depth analysis of how it happened.

The *Four Pillars* started an unbroken line of instrumental developments in which Australia has continued to play a global role. They sowed the seeds that have now led to Australia's involvement in the Square Kilometre Array (SKA) – a major astronomical project with the Murchison Widefield Array (MWA) and the Australian Square Kilometre Array Pathfinder (ASKAP) as its precursors. The authors also speculate, however, on whether the current research and funding environments will still allow new ideas to blossom and whether we are still identifying and mentoring the next generation of systems thinkers needed to implement the new ideas.

R.D. Ekers

Preface

As authors of memoirs of Bernard Mills (Frater, Goss, & Wendt, 2013), Chris Christiansen (Frater & Goss, 2011), Paul Wild (Frater & Ekers, 2012) and Ron Bracewell (Thompson & Frater, 2010), we could not avoid the realisation of their profound effect on the development of (imaging) radio astronomy on a global scale and the fact that they were a unique group of pioneers whose stories should be brought together (see Fig. 1).

Bob Frater and Miller Goss had first-hand interactions with the *Four Pillars* during the early 1960s until their deaths. Bob Frater, as an author on all four of the memoirs, saw the incredible influence these men, his mentors, had had on his life and career. They, in turn, were greatly influenced by a remarkable individual who had been their scientific leader and mentor in their early careers – Joseph Lade Pawsey.

The contributions of each of the *Four Pillars* to the development of radio astronomy were significant in their own right. Mills is remembered for the invention of the cross-type radio telescope that now bears his name and for his contribution to the understanding of the nature of discrete radio sources. He is also remembered for his prolonged battle with one of the giants of radio astronomy, Martin Ryle of Cambridge, over the validity of the radio survey source count data that Ryle was using to base conclusions over which cosmologic model was correct: either the “Big Bang” or “Steady State” model. This was a period when astronomers and theorists were just awakening to the potential of radio astronomy to shed new light on the nature of the universe. Christiansen is remembered for his invention and designs of array-type telescopes and for his application of earth rotational synthesis to produce high-resolution images. His influence, both direct and indirect, extended to the design of radio telescopes throughout the world. Wild is remembered for his masterful joining of radio observations and theory to elicit the nature of the solar atmosphere. His invention of the major classification types of solar radio bursts has stood the test of time and is still in use today as the standard classification. Wild’s work dominated the field of solar radio astronomy for over three decades.

Fig. 1 The authors (L-R) Miller Goss, Harry Wendt and Bob Frater sitting down to plan the Four Pillars in July 2014 at the CSIRO offices in Lindfield, Sydney

He is also remembered for his leadership of the Commonwealth Scientific and Industrial Research Organisation (CSIRO) later in his career. Finally, Bracewell is remembered for his contribution to the development of theory and mathematical techniques used to form images from radio observations. These techniques underpin all of radio astronomy imaging today as well as extending to fields as diverse as medical imaging.

In themselves, each of the individual contributions is remarkable. However, even more remarkable is the fact that they evolved from one group, working in Australia immediately after World War II (WWII). At that time Australia had a population of just over seven million people and none of the Australian Universities even offered PhD-level qualifications. The technology trigger for this rapid period of development was the development of radar during WWII. This provided the technical foundation on which the *Four Pillars* flourished under the scientific leadership of Pawsey. While there have been enormous individual contributions in the development of radio astronomy and, in some cases, these have been recognised with the Nobel Prize, the summed contribution of the *Four Pillars* is equally significant and certainly not as well shared or understood. The legacy created by the *Four Pillars* is widespread not only in radio astronomy but also in fields as far reaching as the development of Wi-Fi. The story contains many remarkable elements including lessons on the process for creating environments in which research can flourish.

The aim of this book is to share this story with a wider audience with an interest in astronomy and science. Chapter 2 provides an introduction to the science of radio astronomy and a brief background to the history of development leading up to the formation of the CSIRO Radiophysics Laboratory in Sydney, Australia. The subsequent chapters introduce each of the *Four Pillars*.

Chapter 7 discusses the influences that the *Four Pillars* had not only on radio astronomy but more broadly on other sciences and on engineering. We conclude with a discussion of the environment and leadership that led to this remarkable period of scientific development and the implications for research today. In drawing these together, we have a story which provides the foundations for the Australia Telescope, Wireless LAN developments, the Square Kilometre Array (SKA) and significant contributions to all the large international radio astronomy facilities operating in the twenty-first century.

We wish to thank the many people we had discussions with during the preparation of the memoirs and of this book: Mark Bracewell, Wendy Bracewell, Ron Ekers (FRS), David Ellyard, Ellen Bouton, Tim Christiansen, Larry D'Addario, Kent Price, Anne Green, Bob Hewitt, Claire Hooker, Crys Mills, Laurel Davidson, Bob Hayward, John Brooks, Mal Sinclair, Anne Manefield, Christine van der Leeuw, Lewis Ball, Dick Hunstead, Ken Kellermann, Bob Lash, Bruce McAdam, Wayne Orchiston, John O'Sullivan, Hastings Pawsey, Martin Y. Smith, Ron Stewart, Dick Thompson, Jasper Wall, Woody Sullivan, the late Sally Atkinson and Stephen White. Special thanks for extensive, detailed comments on the entire text to Tania Burchell, former assistant director of the National Radio Astronomy Observatory for Education and Public Outreach, and Professor Nicole Gugliucci of Saint Anselm College Department of Physics.

The authors thank Robyn J. Harrison for her expert editing, often at the last moment, as well as valuable advice.

We made extensive use of the University of Sydney Archives, the National Archives of Australia, the National Radio Astronomy Observatory Archives as well a number of interviews recorded by Woody Sullivan and R. Bhathal. We are grateful to the CSIRO for images provided courtesy of the CSIRO Radio Astronomy Image Archives and particularly the help of Jessica Chapman. We also wish to thank the Royal Society, the *Historical Records of Australian Science* and *The Journal of Astronomical History and Heritage* for permission to use material published in the memoirs of the *Four Pillars*.

Finally we thank the CSIRO for assistance during the publication of this book. Both Dr Douglas Bock and his predecessor, Dr Lewis Ball, (Director of CSIRO Astronomy and Space Science and Director of the Australia Telescope National Facility) have been enthusiastic supporters in providing funds for the editorial tasks during the last few years.

Lindfield, NSW, Australia R.H. Frater
Socorro, NM, USA W.M. Goss
Vaucluse, NSW, Australia H.W. Wendt

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About the Cover

The pier with Bob Frater's signature and cutouts of the other signatures that appear on other piers

In 1955, Australian radio astronomer Ron Bracewell, one of the *Four Pillars*, joined the faculty of Stanford University in California. There he established a Radio Astronomy Institute and developed an observatory. He built an array for solar observations using 32 ten-foot-diameter dish antennas, each of which was mounted on a concrete pier or pillar. Bracewell invited visiting astronomers to chisel their names into a pier, accumulating some 220 "signatures" over the course of 20 years.

In 1980, after two decades of use, the antenna array was closed. In 2012, ten of the piers were sawed off and shipped to the Karl G. Jansky Very Large Array in New Mexico to become part of a unique sundial designed by W.T. Sullivan III. As a tribute to radio astronomy, the markers of the sundial show not only the time of day and time of year but also the current location in the sky of Centaurus A, Cygnus A and Cassiopeia A, three prominent and important objects for radio astronomers.

The cover photograph is a small section of the sundial, with one of the antennas of the Array in the background. The *Four Pillars* (as well as the first author of this book and Joseph Pawsey, "the Grand Old Man of Radio Astronomy") had each signed one of the piers of the Stanford Array. Their signatures can be found on the pillars of this sundial.

Contents

Chapter 1
Introduction

The Significance of the *Pillars*

On 23 September 2013, the Ron Bracewell Radio Sundial officially opened near the visitor centre at the site of the Karl G. Jansky Very Large Array in New Mexico, USA. This unique instrument was designed by Woody T. Sullivan III and funded by donations from the Friends of the Bracewell Observatory and Associated Universities, Inc. The pillars of the sundial are the concrete piers that originally supported the dishes of the crossed-grating array that was built by Bracewell at Stanford. Over the years, these piers were used as a type of "guestbook", where Bracewell invited visiting radio astronomers to chisel their names into the concrete piers (see Fig. 1.1).

During the two decades until the observatory closed in 1980, over 220 signatures were collected on the piers forming a who's who of the pioneers of early radio astronomy. Ten of the original piers have been preserved and now form part of the new Radio Sundial (see Figs. 1.2 and 1.3). The design of the Radio Sundial is unique as it functions not only as a conventional sundial, but also allows visitors to locate the approximate positions in the sky of three discrete radio sources (Centaurus A, Cygnus A and Cassiopeia A) that played important roles in early radio astronomy. This creation is a fitting tribute to Bracewell who developed many of the mathematical techniques that are used in imaging by radio telescopes like the Karl G. Jansky Very Large Array visible in the background of the cover photograph.

While over 200 names appear on the piers of the Radio Sundial, in this book we have chosen to focus on four: Bernie Mills, Chris Christiansen, Paul Wild and Ron Bracewell. They were unique as they started their journey in a small team immediately after WWII under the mentorship of Joe Pawsey. They would go on to establish worldwide reputations as the leaders in their fields, and the instruments and techniques they developed would underpin much of modern radio astronomy.

R.H. Frater et al., *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, Astronomers' Universe, DOI 10.1007/978-3-319-65599-4_1

Fig. 1.1 Ron Bracewell touching up the signatures chiselled on one of the concrete piers at Stanford

Australia Helps Lay the Foundation for Radio Astronomy

How such a concentration of scientific talent formed, particularly in a field of fundamental science and in a relatively isolated country like Australia immediately after WWII, is worthy of consideration. The necessity of developing radar in Australia during WWII was the catalyst for the formation of the Radiophysics

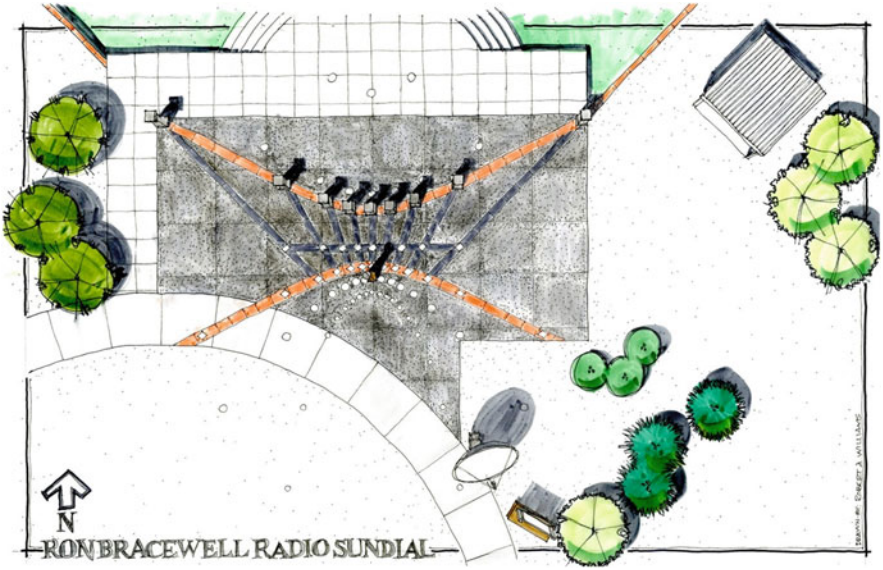

Fig. 1.2 A schematic plan of the Ron Bracewell Radio Sundial located at the Karl G. Jansky Very Large Array in New Mexico, USA, showing the configuration of the piers from the original crossed-grating array. Nine of the piers make up the markers of the Radio Sundial, with the tenth pier supporting a restored version of a dish from the original Stanford crossed-grating array (*lower centre*)

Laboratory (RPL) of the then Council for Scientific and Industrial Research (CSIR, later to become the Commonwealth Scientific and Industrial Research Organisation (CSIRO)). The leadership of Sir David Rivett, who held a strong philosophy of supporting basic research and finding the best individuals and giving them their head, established a culture that supported the early development of radio astronomy. Unlike both the USA and the UK, Australia did not have strong university research programmes underway to which the wartime radar researchers could return following the cessation of hostilities. Rivett's decision to retain the radar research team, but to refocus its activities on peacetime research, was key to forming what would be the largest radio astronomy research team in the world in the 1950s.

Another key factor was the unique marriage of the entrepreneurial leadership style of Taffy Bowen, who took over as Chief of Radiophysics in 1946, and the scientific leadership of Joe Pawsey, head of the radio astronomy group. This powerful combination, with Bowen playing the role of the outward charismatic leader of the Radiophysics Division, coupled with Pawsey's deep physical scientific understanding and his mentoring approach, set up a unique environment where researchers, including the *Four Pillars*, could flourish.

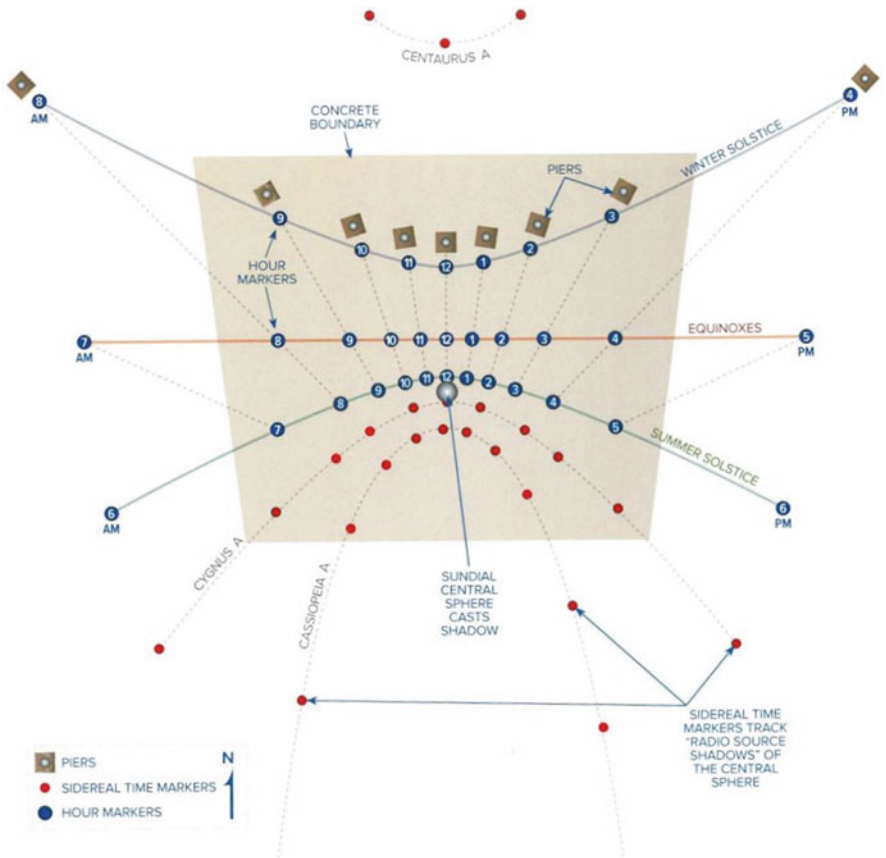

Fig. 1.3 A plan of the Bracewell Radio Sundial showing the locations of the piers and central gnomon, which is the part of a sundial that casts the shadow. The sundial can also be used to locate the position in the sky of three key discrete radio sources. The *red dots* mark the sidereal time of the radio source shadows (if they were visible). By standing on a marker close to the current sidereal time and looking back towards the gnomon sphere, the viewer will see the approximate position in the sky of the radio source (Courtesy of NRAO)

Pawsey (see Fig. 1.4) emphasised “research teams”, rather than the efforts of individuals; this structure resulted in harmonious personal relationships among members of the team.

Frank Kerr (1963), one of the first appointees at RPL from early 1940, has written:

> Pawsey built up a powerful group which has made major contributions to almost every branch of radio astronomy…He was an inspiring research leader, with a particular skill in developing the independence and self-reliance of the members of his team to a point where many of them have achieved substantial reputations of their own. He expected his men to live up to his own high standards in their work.

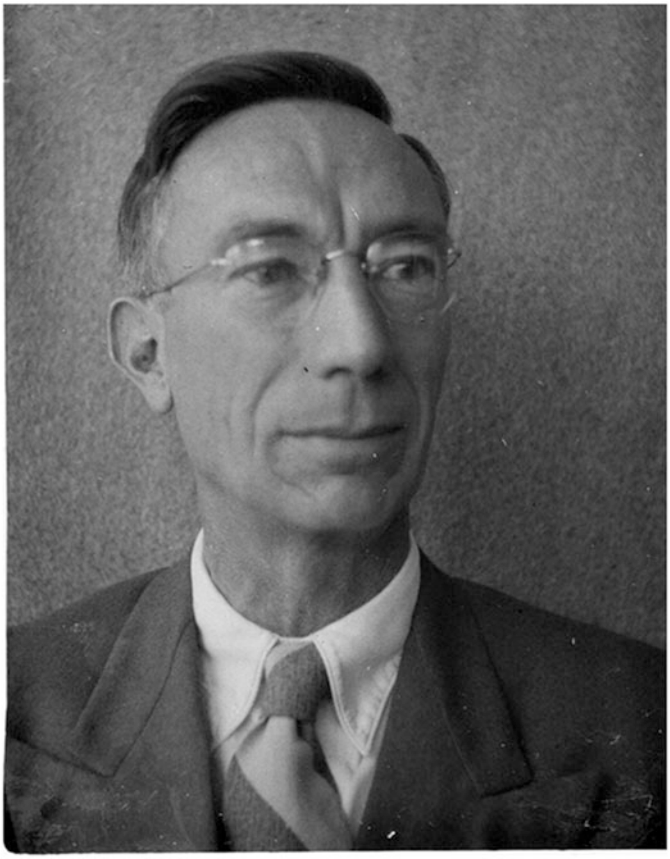

Fig. 1.4 Joseph Pawsey in 1957 (Courtesy of Pawsey family collection)

Pawsey (1961) described the necessary ingredients for successful discovery:

> It should be noted that [this process] can only be followed effectively in a well-organized scientific organization in which the scientific direction can very quickly make decisions and supply facilities for the really promising developments. In all too many cases elsewhere, the energies of scientists are taken up in advertising the potentialities of their prospective investigations in order to obtain any support at all. The result is a neglect of the unspectacular preliminary probing investigations which are often such a vital ingredient in success.[1]

This book is about four men, Bernie Mills, Chris Christiansen, Paul Wild and Ron Bracewell, who were allowed their "unspectacular preliminary probing investigations" in this rich, nurturing environment. They rose up as pillars to support this

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[1] Frank Kerr later wrote (1984): "[In Pawsey's group] simple equipment lead to the development of more and more complex equipment in a step-by-step manner as each stage produced new phenomena that needed to be elucidated".

new branch of astronomy, each in his own right, making important contributions to the theory and practice of observing the universe through the radio spectrum, a science that had its beginnings with the discovery by Karl Jansky in 1931 of radio waves coming from space.

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Chapter 2

Beginnings: Some Basics and Some History

Astronomy and the Electromagnetic Spectrum

Astronomy, one of the oldest sciences dating back to the earliest civilisations, is a natural science. Astronomers seek to understand the nature of the universe based on observational and empirical evidence. During nearly all of this history, observations were made by looking at light in the night sky from the stars and nebulae, using the naked eye and later, the optical telescope. Light as perceived by the naked eye is a form of electromagnetic radiation, but this visible light makes up only a very small part of this spectrum: the rest is effectively invisible to the human eye (see Fig. 2.1).

In 1800, the English astronomer William Herschel (1738–1822) realised that there were some types of light rays that could not be seen. He discovered this when he attempted to measure the temperatures of different colours of sunlight using a thermometer. By using a prism to split sunlight into its colour spectrum (red, orange, yellow, green, blue, indigo, and violet), he noted that the colour red (longer wavelength) gave a higher temperature than violet (shorter wavelength), but that the thermometer recorded its highest temperature just outside the red end of the spectrum where no light was visible. He postulated that the cause of this temperature rise was "unseen" light, which he called "calorific rays". Today these are known as infrared radiation.

Soon after this, the German chemist and physicist Johann Ritter (1776–1810) noticed that, just outside the other end of the light spectrum (violet – shorter wavelength), invisible rays appeared to induce certain chemical reactions. This was the discovery of ultraviolet radiation.

In 1845, the English scientist Michael Faraday (1791–1867) noted that polarised light travelling through a transparent material changed its direction of polarisation in response to the application of a magnetic field. Polarisation refers to the direction in which light waves oscillate. This became known as the "Faraday effect" and was a key stepping stone in determining that light was, in fact, a form of electromagnetic radiation.

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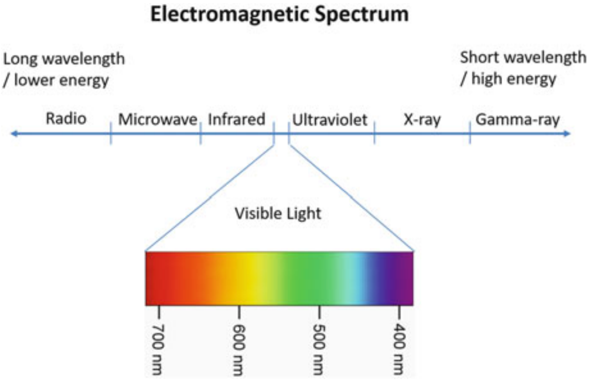

Fig. 2.1 Visible light represents only a small portion of the electromagnetic spectrum

During the 1860s, the Scottish scientist James Clerk Maxwell (1831–1879) explored the behaviours of waves in both magnetic and electric fields. He realised that these theoretical waves, regardless of their wavelength, should all travel at the speed of light and that they were, in fact, the same phenomena. The equations he developed predicted the existence of the electromagnetic spectrum where all wavelengths travel at the speed of light. This provided an explanation for the existence of the "unseen" light rays found by Herschel and Ritter and also predicted that these "unseen" rays should extend further along the spectrum to longer and shorter wavelengths than just the infrared and ultraviolet wavelengths.

The Beginning of Radio Astronomy[1]

In 1886 the German physicist Heinrich Hertz (1857–1894) attempted to verify Maxwell's prediction of very long wavelength electromagnetic radiation. In 1887 he successfully detected and measured what are now known as radio waves. The frequency of these waves was measured in cycles per second, and this unit of measurement is now referred to as a Hertz (Hz) in honour of their discoverer. High frequency relates to short wavelengths, whereas low frequency refers to long wavelengths. Following Hertz's discovery, there was an initial flurry of attempts[2] to

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[1] For the reader interested in a deeper understanding of the emergence of radio astronomy, the definitive text on this topic is Sullivan, W. T. 2009. *Cosmic noise: a history of early radio astronomy*, Cambridge, Cambridge University Press.

[2] Examples of papers published during this period: Wilsing, J. & Scheiner, J. 1896. On an attempt to detect electrodynamic solar radiation and on the change in contact resistance when illuminating two conductors by electric radiation. *Annalen der Physik und Chemie*, 59, 782–792.; Deslandres, H. & Decombe, L. 1902. On the search for Hertzian radiation emanating from the sun. *Comptes Rendus Hebdomadaries des Seances del l'Academie des Sciences*, 134, 527–530.; Nordmann, C. 1902. A search for Hertzian waves emanating from the sun. *Comptes Rendus Hebdomadaries des Seances del l'Academie des Sciences*, 134, 273–275.

detect radio waves from the sun, none of which were successful. Interest quickly waned despite rapid improvements in receiver technology (and hence sensitivity) for the communications industry, which would have made detection of radio waves from the sun much easier.

To detect electromagnetic waves, the receiving device (antenna) generally needs to be about the same size as the wavelength it is designed to detect. Visible light has a very short wavelength ranging from 390 to 700 nm, whereas the radio frequency band covers wavelengths from 1 mm to 100 km. This means that, to achieve a similar resolution to visible wavelengths, a radio antenna needs to be much larger than its optical counterpart.[3]

Karl G. Jansky

The study of radio astronomy effectively began with a serendipitous discovery by Karl Guthe Jansky (1905–1950) while he was working at Bell Laboratories in the USA in 1931–1932 (see Fig. 2.2). Jansky was examining the sources of interference that affected short-wave trans-Atlantic radio communications at a frequency of 20.5 MHz (14.6 m wavelength). He had managed to isolate a component of interference that he called "hiss type static". At first he believed the source of this static was related to distant thunderstorms. Further examination showed that the source appeared to be coming from a fixed position in the sky moving over a roughly 24-h period with the earth's rotation but did not appear to be associated with the sun. By examining over a year's worth of records, he made the crucial discovery that the period of movement was not exactly 24 h. Over the course of a year, the arrival time of the peak signals changed by a day. An astronomer would immediately recognise the significance of this: a fixed celestial coordinate will rise 4 min earlier each day as a result of the earth orbiting the sun. Over the period of a year, this adds up to a shift of a full day. Jansky recognised that this meant that his "hiss type static" had to be coming from a direction that was fixed in space; he therefore concluded that the source must be extraterrestrial. The publication (Jansky, 1933) of his results heralded the beginning of a new age of astronomy.

Until 1933, astronomy had only been conducted in the "visible" part of the electromagnetic spectrum. The revelation that celestial objects could now be detected not only in the relatively narrow bandwidth available to the human eye but also at radio wavelengths led to a revolution in astronomy over the next half-century. This revolution was led by engineers and physicists rather than astronomers and spread across the electromagnetic spectrum from radio to X-ray and gamma-ray wavelengths, opening whole new vistas of discovery and expanding the known universe.

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[3] For an explanation of antennas, aerials and radio telescopes, see Appendix A, "What is a radio telescope?"

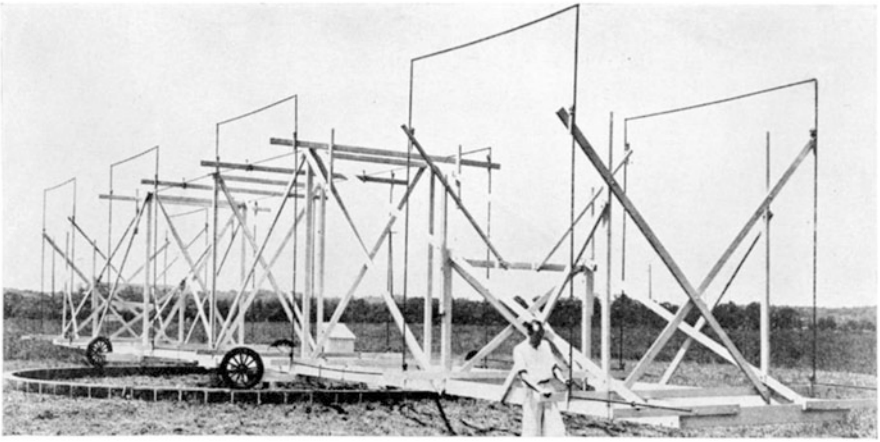

Fig. 2.2 Karl Guthe Jansky (1905–1950) and the "merry-go-round" antenna at Bell Telephone Laboratories' Holmdel Fields station in New Jersey in the early 1930s. Jansky used this instrument, a Bruce Curtain type aerial, to investigate non-terrestrial radio emission at 20.5 MHz in 1931–1933, thereby initiating a new research field that would become known as "radio astronomy" (CSIRO Historical Radio Astronomy Image Archives B3985-1)

Despite extensive publicity about Jansky's discovery, including a front-page story in the *New York Times* on 5 May 1933, there was initially a distinct lack of interest in exploiting the new technique. Radio engineers and physicists saw this source of "noise" as nothing more than an interesting curiosity; astronomers were not familiar with the new technology and the implications. Jansky himself soon moved on to other research topics.

Grote Reber

In 1937 amateur radio enthusiast Grote Reber (1911–2002) built a radio telescope[4] (see Fig. 2.3) in his mother's backyard in Wheaton, Illinois, USA, that enabled a serious follow-up to Jansky's discovery. In an amazing effort, constructing all his own equipment and observing overnight while also working full time, Reber was able to confirm Jansky's discovery (Reber, 1940a, b). He went further, surveying the sky at 160 MHz (Reber, 1944) and producing a contour map of radio frequency emission closely aligned to the shape of the Milky Way that showed an intensity concentration towards the centre of the Milky Way. Reber's image also showed concentrations in the directions of the constellations Cygnus, Cassiopeia, and Canis Major, which he interpreted as projections of the Milky Way. For the first time,

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[4] The name "radio telescope" was not used until nearly a decade later. In 1937 this was still referred to as an "antenna" or "aerial".

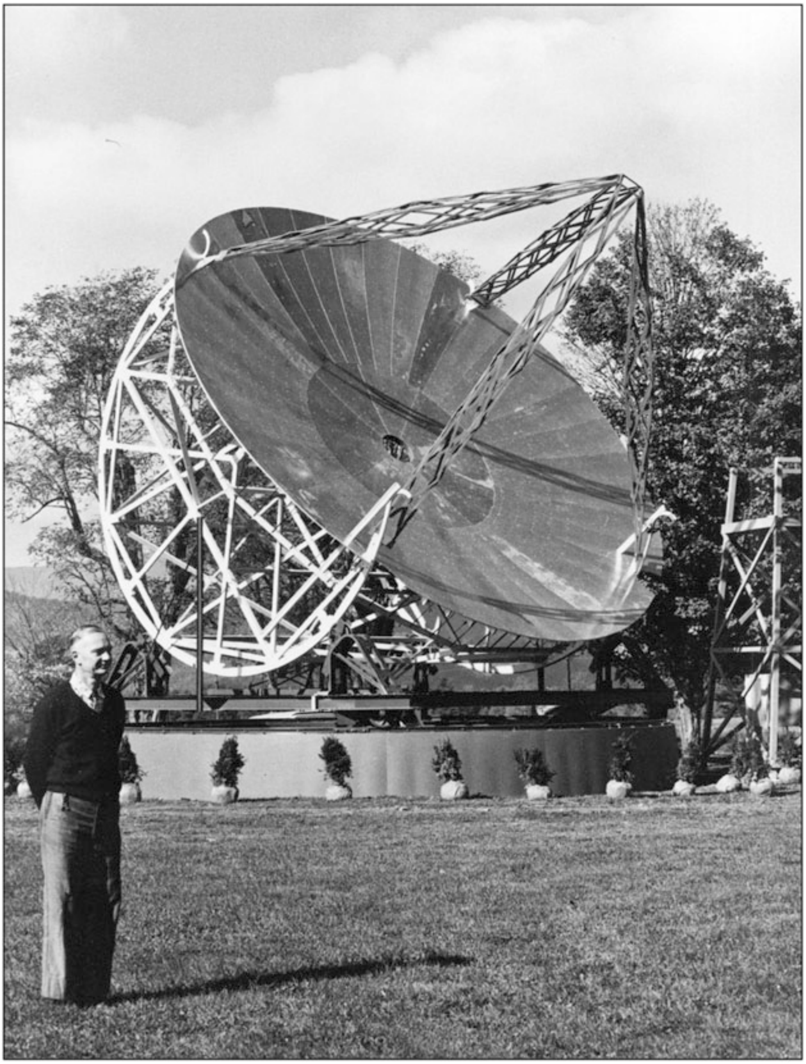

Fig. 2.3 Grote Reber standing next to the parabolic antenna that was originally set up in the backyard of his home at Wheaton, Illinois, in 1937 and used over the next decade to study solar and Galactic emission at a number of frequencies. This antenna is now on display at the Green Bank Observatory, West Virginia, formerly part of the National Radio Astronomy Observatory (NRAO) (CSIRO Radio Astronomy Historical Photographic Archives R10865)

astronomers were presented with a more familiar visual representation of what the radio engineers were "seeing" at radio frequencies. Reber also announced that he had detected radio emissions from the sun, the first published successful detection of "solar noise".

World War II

The invention of radar in the lead-up to World War II not only created a technology that has been credited with helping to determine the outcome of the war, but also allowed major advances in radio frequency technology and produced a whole cadre of engineers and scientists familiar with its application.

James Stanley Hey (1909–2000) was working for the Army Operational Research Group in the British military; he had been assigned to investigate German jamming of British radar. In another serendipitous event, the sun, in 1942, was producing major solar outbursts. In the course of his investigation, Hey noted that intense “noise-like” interference appeared to be coincident with the movement of the sun across the sky over the period of a day. The identification was confirmed by the Royal Greenwich Observatory as the solar physicists reported a large sunspot had been the source of a prominent solar flare on 28 February 1942. Hey (1942) published his findings in a classified military report.

Only 4 months after Hey published his secret report, George C. Southworth (1890–1972), working at Bell Labs in the USA, also detected the sun at the much higher frequency of 9400 MHz. Unlike Hey, his investigations were the result of a purposeful search for solar emission and these results were also published in a classified report due to wartime controls. The secrecy surrounding these wartime detections was the reason that Reber’s later 1943 detection became the first publicly available report of the detection of radio waves from the sun some 50 years after Hertz’s discovery.

In the midst of the global crisis of WWII, astronomy stood ready to be transformed. Over the course of the next decade, together with England, Australia would become an undisputed research leader in the new field of radio astronomy.

Radiophysics Laboratory

In 1926 the Australian government established a semi-autonomous body known as the Council for Scientific and Industrial Research (CSIR)[5] whose purpose was to promote scientific research for the benefit of primary and secondary industries, and to encourage the pursuit of “pure” scientific research. Radio research was one area considered of vital importance to communications on an isolated and sparsely populated island continent.

The CSIR Radio Research Board was formed in 1926 and chaired by John P.V. Madsen (1878–1969) who was the first professor of electrical engineering at

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[5] For the official history of the establishment of the CSIR, see Schedvin, C. B. 1987. *Shaping science and industry—a history of Australia’s Council for Scientific and Industrial Research, 1926-1949*, Sydney, Allen & Unwin Australia Pty Ltd.

the University of Sydney. Although with modest beginnings, research was supported at both the University of Sydney and the University of Melbourne.

Before 1948, Australian universities did not offer doctoral training. Anyone wishing to undertake advanced studies needed to do so overseas. For radio research, this inevitably meant a "colonial Australian" studying either under Edward Appleton at King's College, London, or under John A. "Jack" Ratcliffe at the Cavendish Laboratory, Cambridge. Appleton had been awarded a Nobel Prize in 1947 for his 1927 confirmation of the existence of the ionosphere, and Ratcliffe and Maurice Wilkes had conducted extensive research into the propagation of very long wave radio in the ionosphere. The ionosphere is the upper region of the Earth's atmosphere comprised of charged particles. The influence, particularly that of Ratcliffe, on Australian Radio Astronomy would be far-reaching and will be discussed later.

Despite the tyranny of distance, by the start of WWII Australia had established an international reputation for ionospheric research. The emerging scientific leader of this community was David Forbes Martyn (1906–1970) who had emigrated from the UK to Australia after completing his PhD at the Royal College of Science in London in 1928.

In February 1939, with hostilities in Europe inevitable, the British government sent a request through the Australian High Commissioner that Australia send its "best qualified physicist" to England so that secret research of fundamental significance could be shared. Martyn was chosen for this task, which resulted in his learning the British secrets of radar.

On Martyn's return in August 1939, the CSIR established a new division called the Radiophysics Laboratory (RPL) specifically to conduct radar research in close liaison with British laboratories and the Australian military. The new division fell under the governance of the newly formed Radiophysics Advisory Board, of which Madsen was appointed the first chairman. Martyn was appointed head of the division, and the laboratory was housed in the newly established National Standards Laboratory on the grounds of the University of Sydney (see Fig. 2.4). The senior scientists initially appointed were Oliver Owen Pulley (1906–1966), George Hector Munro (1901–1994), Jack Hobart Piddington (1910–1997) and Joseph Lade Pawsey (1908–1962).

With Madsen at the University of Sydney and Thomas Howell Laby (1880–1946) at the University of Melbourne training new physicists and engineers, RPL numbers grew rapidly and by war's end some 300 staff were employed, 56 of whom were research scientists involved in research, development and manufacture of radar equipment (see Fig. 2.5). Their expertise grew as they not only reproduced British designs but designed and manufactured unique equipment more suited to the Asia-Pacific theatre and expanded into operational research and vacuum-tube design (see Fig. 2.6).

In the later part of 1940, management changes were afoot. Madsen had decided there was a need to strengthen scientific liaison with Britain. He originally intended to send Martyn but in a last-minute decision decided that he himself would travel to the UK. He had previously persuaded Frederick William George White (1905–1999) (see Fig. 2.7), who had been the professor of physics at Canterbury

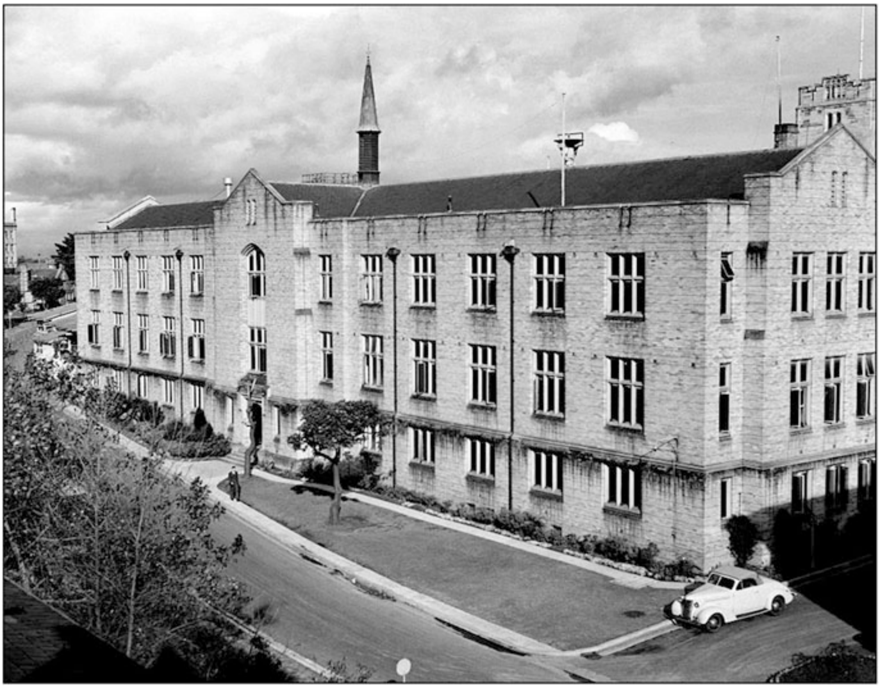

Fig. 2.4 The Radiophysics Laboratory on the grounds of the University of Sydney in 1952. This view is of the western side of the building that had the Radiophysics entrance. The eastern side housed the National Standards Laboratory. The building is now known as the Madsen Building (CSIRO Radio Astronomy Historical Photographic Archives 2941-R)

College, New Zealand, to come to Australia on a temporary basis to cover Martyn's absence. With Madsen's departure, White now found himself as acting chairman of the advisory board. Some personal indiscretions by Martyn had led to his falling from favour with the CSIR Executive, and he was relegated to reporting to White. In 1942, the then Chief Executive Officer of the CSIR David Rivett (1885–1961) decided to transfer Martyn to the post of director of an army operational group, and White was subsequently appointed the new head of the Radiophysics Division in October 1942, serving until January 1945.

White proved to be a very effective leader and manager, guiding the laboratory through rapid development in the complex wartime environment. In mid-1943 he toured radar research establishments in both Britain and the USA. It was during his visit to the MIT Radiation Laboratories in the USA that he met Edward G. "Taffy" Bowen (1911–1991) (see Fig. 2.8). Bowen had extensive experience in radar development[6] and also was visiting the Massachusetts Institute of Technology as part of a

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[6] For a description of Bowen's wartime activities, see Bowen, E. G. 1987. *Radar days*, Bristol, UK, Institute of Physics Publishing.

Fig. 2.5 Joe Pawsey and Frank Kerr working inside the Radiophysics testing laboratory on the grounds of the University of Sydney (date unknown, likely before 1946) (CSIRO Radio Astronomy Historical Photographic Archives B8880-2)

programme to share the secrets of the cavity magnetron. White convinced Bowen to join the RPL as his Deputy Chief and soon after to take over as Chief (June 1946) after White was appointed to the CSIR Executive Committee. Bowen had been one of Watson Watt's team that developed the Chain Home radar defence system in the UK in the late 1930s. This radar system had played a major role in the UK victory in the Battle of Britain in 1940.

Birth of Radio Astronomy in Australia

With WWII drawing to a close, the potential role of the Radiophysics Division in peacetime was being considered. Rivett[7] was a strong advocate of separating "secret" research from the publicly available research role of the CSIR and favoured a return to independence and a greater focus on basic research. Bowen prepared a 26-page report on the "Future Programme for the Division of Radiophysics" which was presented at the 35th session of the Council of the

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[7] Rivett became chairman of the CSIR in 1946. In 1948 he was the subject of an unpredicted political attack in the parliament by the conservative parties hoping to destabilise the Labor Government by linking Rivett's philosophy of openness in scientific research with communist sympathies. Rivett resigned as Chairman of the CSIR when the CSIRO was founded in May 1949.

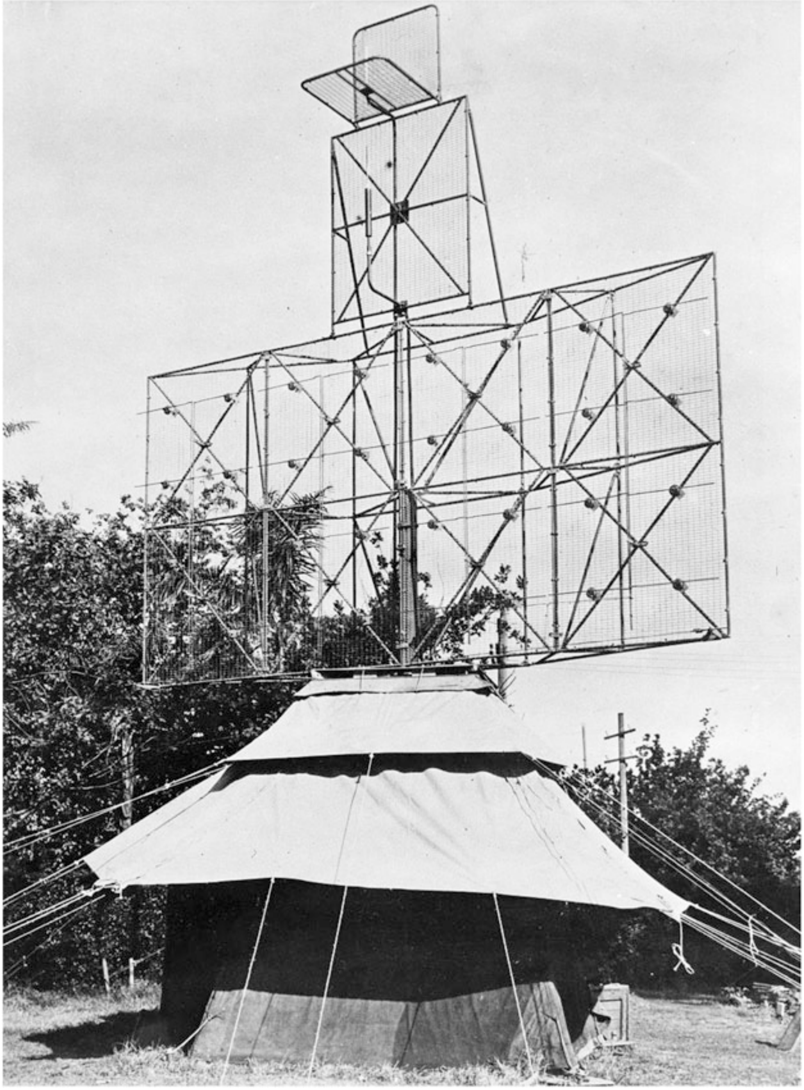

Fig. 2.6 A lightweight air warning (LW/AW) 200 MHz radar with identification friend or foe (IFF) transponder designed by the Australian Radiophysics group, New South Wales Government Railways and the RAAF. This was the most successful radar set produced in Australia in the later part of 1942 and used by the RAAF and US Army Air Forces throughout the Southwest Pacific theatre during the war (CSIRO Radio Astronomy Historical Photographic Archives B10182-3)

CSIR in July 1945. The report proposed a wide range of peacetime research topics, including a short paragraph titled "Study of Extra-thunderstorm Sources of Noise (Thermal and Cosmic)". The report was well received and endorsed by the Executive. This soon led to the formation of a number of small independent research

Fig. 2.7 Sir Frederick William George White (1905–1999). The New Zealander moved to Australia in March 1941. He headed the Division of Radiophysics from October 1942 to January 1945 and then went on to be CEO and then Chairman of the CSIRO. He was one of the major figures of science in Australia in the twentieth century and was the principle architect of the CSIRO after WWII (CSIRO Radio Astronomy Historical Photographic Archives B11415)

teams focusing on air navigation, cloud physics, electronic computers, and the investigation of radio noise sources as noted above. The radio noise group was led by Joe Pawsey (see Fig. 2.9). From these very humble beginnings, Pawsey's group would go on to become one of the most accomplished radio astronomy groups in the world.

The CSIR itself would also undergo some fundamental changes. Rivett became increasingly disillusioned with what he saw as political interference with the role of the CSIR, and he subsequently elected to retire following the proclamation of a new act in May 1949 to reconstitute the role of the new Commonwealth Scientific and Industrial Research Organisation (CSIRO). He was replaced as Chairman by the

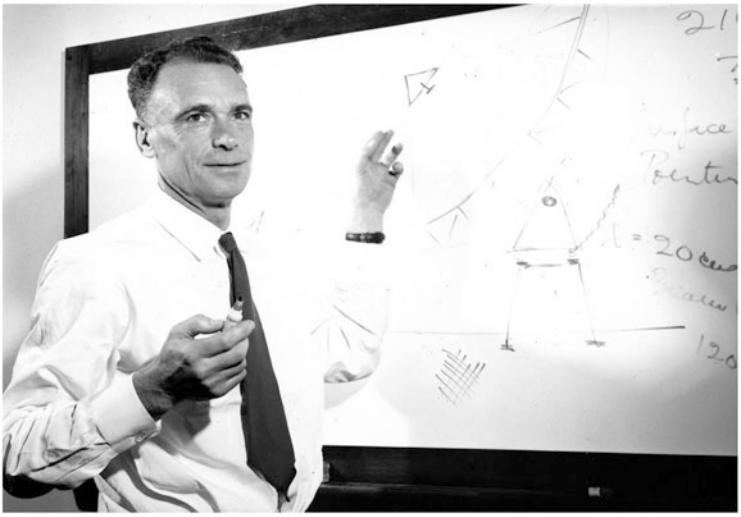

Fig. 2.8 Edward G. "Taffy" Bowen (1911–1991). The Welshman was part of the original team with Watson Watt at the birth of UK air warning radar in the 1930s. He was a member of the Tizard mission that shared the secrets of radar with the allies, arriving in Sydney in January 1944 after a period in the USA. He became the Chief of the Division of Radiophysics from May 1946 until his retirement in 1971 and was the father of the 64 m Parkes Radio Telescope project. (CSIRO Radio Astronomy Historical Photographic Archives R6429-2)

Australian veterinary scientist Ian Clunies Ross (1899–1959), and White was appointed as Chief Executive Officer.

Rivett's decision at the end of WWII to retain a highly trained group of scientists within the Radiophysics Division, but to refocus them on more basic research and peacetime applications, was profound. This, coupled with the experienced leadership of White and Bowen, created an environment within which Pawsey's group could thrive.

Schedvin (1987) characterised Sir David Rivett as "the high priest of scientific attainment and of the quest of knowledge as an independent ethical principle". Sir Fred White, who became CEO of CSIRO in 1949 at age 44, was "the principle architect of CSIRO after the war. He was also Rivett's spiritual successor". Sir Ian Clunies Ross was "the people's scientist, the supporter of research projects in the biological field...". All played major roles in the foundation of radio astronomy at the CSIR in late 1945.

These events marked the birth of radio astronomy in Australia. Bowen and Pawsey would go on to develop an amazingly talented group of engineers and physicists who would become the new breed of "radio" astronomers. While the focus of this book is on four key members of this group, we must mention the major contributions made by other members of the early Radiophysics group. John Bolton

Fig. 2.9 Joseph "Joe" Lade Pawsey (1908–1962) was the founding leader of the Australian radio astronomy group and also the second Director of the National Radio Astronomy Observatory (NRAO) in the USA for a short period in 1962 before his untimely death on 30 November 1962 at the age of 54 (CSIRO Radio Astronomy Historical Photographic Archives B7454-2)

(1922–1993)[8] led the pioneering team of Gordon Stanley (1921–2001)[9] and Bruce Slee (1924–2016)[10] that proposed the first optical identifications of three discrete radio sources. The results of their research were published in *Nature* (1949),

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[8] For details see Wild, J. P. & Radhakrishnan, V. 1995. John Gatenby Bolton. 5 June 1922–6 July 1993. *Biographical Memoirs of Fellows of the Royal Society*, 41, 72–86.

[9] For details see Kellermann, K. I., Orchiston, W. & Slee, B. 2005. Gordon James Stanley and early development of radio astronomy in Australia and the United States. *Publications of the Astronomical Society of Australia*, 22, 13–23.

[10] For details see Orchiston, W. 2005. Sixty years in radio astronomy: A tribute to Bruce Slee. *Journal of Astronomical History and Heritage*, 8, 3–10.

prompting the beginning of the journey of understanding the true nature of the "radio stars". In 1955, after leaving radio astronomy to work for a brief period in the Cloud Physics group at RPL, Bolton moved to Caltech in the USA and went on to establish the Owens Valley Radio Observatory. In 1961, he returned to Australia as the first director of the 64 m Parkes Radio Telescope. Frank Kerr (1918–2000),[11] one of the original WWII radar team members, took over the hydrogen line research programme from Christiansen and built this into a major programme of work in Galactic research at Radiophysics and later at the University of Maryland. Alexander Shain (1922–1960)[12] developed the field of low-frequency Galactic radio observations before his untimely death in 1960. Ruby Payne-Scott (1912–1981),[13] another WWII radar team member, made pioneering contributions in understanding solar radio emissions as well as being a co-author with Joe Pawsey and Lindsay McCready of the landmark paper that proposed the principles of the use of the Fourier Transform for image reconstruction in radio astronomy. There are many others who made major contributions in the remarkable first decades of radio astronomy. In this story we have focused on a core group who were highly influenced by Pawsey and who would themselves go on to shape the development of radio astronomy both in Australia and overseas.

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[11] For details see Westerhout, G. 2000. Obituary: Frank John Kerr, 1918–2000. *Bulletin of the American Astronomical Society*, 32, 1674–1676.

[12] For details see Pawsey, J. L. 1960. Charles Alexander Shain (obituary). *Quarterly Journal of the Royal Astronomical Society*, 1, 244–245.

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Chapter 3
Bernie Mills: Cross-Type Telescopes and Discrete Radio Sources

Bernard Yarnton Mills (Fig. 3.1) was born at Manly, New South Wales, on 8 August 1920, the only child of Ellice Yarnton Mills (1882–1945) and Sylphide Mills née Dinwiddie (1890–1962).

Ellice Mills was an architect employed by the Sydney Municipal Council who had immigrated to Australia from England a little before World War I. His mother was a dance teacher from New Zealand.

A precocious child, Bernie was sent to the King's School, a school in the English tradition in Sydney. He was ahead of his age group, skipped a class and again headed his class, which proved difficult socially in a school devoted to sporting ability rather than scholastic prowess.

In 1937, at the age of 16, Bernie began his university studies at the University of Sydney.

Bernie warmed to the university environment where he met people from very different social and political backgrounds and where his intellectual capabilities were challenged. He played chess – somewhat at the expense of his studies – winning University and City of Sydney Championships. During University vacations, he undertook work with several engineering firms where he gained practical experience and exposure to a broad range of workers and left-wing politics, far removed from the environment of his upbringing.

In 1939, he met Russian-born Lerida Karmalsky, a medical student and chess player, who introduced him to the Labor Club. They married in 1942. As with many left-wing students of the time (1941), they both joined the Communist Party. They resigned in disgust after the Russian invasion of Hungary in 1956. (By this time, Bernie had been with the CSIRO for 13 years.)

Bernie was awarded a Bachelor of Science degree in Maths and Physics in 1941 and a Bachelor of Engineering degree with Second-Class Honours in 1943. He was proud of the fact that he and Ron Bracewell (a fellow student who would later become a distinguished radio astronomer – see Chap. 6) had both gone on to great career success with Second-Class Honours degrees.

R.H. Frater et al., *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, Astronomers' Universe, DOI 10.1007/978-3-319-65599-4_3

Fig. 3.1 Bernard Yarnton Mills (Unknown photographer, likely 1963, Royal Society)

The Division of Radiophysics

On completing his studies at the end of 1942, Bernie joined the Division of Radiophysics of the then Council for Scientific and Industrial Research (CSIR – the forerunner to the CSIRO) to work on radar research and development. He worked in the receiver and display group where he contributed to the design of a height-finding radar that was used after the war at Mascot airport in Sydney. The development of this radar was perhaps RPL's (Radiophysics Laboratory) outstanding technical achievement during the war (Minnett 1999).

Joe Pawsey headed the general development and experimental work at RPL at this time. In the short lecture courses he gave on transmission lines and antennas, he promoted a physical understanding rather than the highly mathematical approach that Bernie had been exposed to during his studies. This physical understanding was key in Bernie's career and life.

After the War

After the war, the Division explored the use of a magnetron as a power source for a linear electron accelerator (Bowen, Pulley, & Gooden, 1946). When this project was abandoned, Bernie was given the task of exploring the possibilities of developing the equipment for X-ray work (Home, 2006). This investigation was his first exposure to physics that went beyond Maxwell's equations, providing a practical introduction to relativity and even some quantum physics.

The development was successful and resulted in Bernie's first major publication, "A Million Volt Resonant Cavity X-ray Tube". His project report was submitted as a Master of Engineering thesis and awarded First-Class Honours in 1950.

In late 1947, Bernie was diagnosed with early-stage tuberculosis. Fortunately, this potentially life-threatening condition was detected early, and after 6 months' bed rest, he made a full recovery.

Engineer Becomes Astronomer

The timing of his return to work gave Bernie the choice of continuing with the computer development or joining Pawsey's new radio astronomy group. He jumped at the opportunity to work again with Pawsey.

Bernie described his entry into the group:

> I began with some necessary study of astronomy, some equipment development, and assistance to Chris Christiansen and Don Yabsley in their observations of the 1948 Solar eclipse (Christiansen, Yabsley, & Mills, 1949a, b). This led to my first paper in radio astronomy, as the junior author! However, I had to get started on a project of my own, and Pawsey suggested two possibilities: to try and detect the H-line [the hydrogen line at a wavelength of 21 cm] which had been predicted by van de Hulst, or to use the swept-lobe solar interferometer[1] being developed by Little and Payne-Scott (1951) to study the mysterious radio sources which John Bolton had made using his own cliff-top interferometer.[2] Pawsey was very dubious about the future of this form of interferometry and felt that the two-antenna interferometer of Payne-Scott and Little offered much the better prospects for accurate positions and identifications even though the antennas were smaller

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[1] The swept-lobe interferometer was a Michelson interferometer (see Appendix A) with a response pattern that could be moved back and forth over the sun at a rate of 25 times a second. With the sea-cliff interferometer, the motion of the response pattern was limited to the slow rate governed by the rotation of the earth (scan duration of the sun about 2 min of time).

[2] The sea-cliff interferometer (see Appendix A) had first been used by McCready, Pawsey and Payne-Scott (1947) to investigate the source of solar radio emission. This was in fact the first use of interferometry in radio astronomy. Bolton and his team at Dover Heights went on to use the sea-cliff interferometer for the pioneering work in investigating the cosmic radio sources, and this resulted in the first three optical identifications of discrete radio sources, two extragalactic and one the Crab Nebula, the remnant of the supernova of 1054 (Bolton, Stanley, & Slee, 1949).

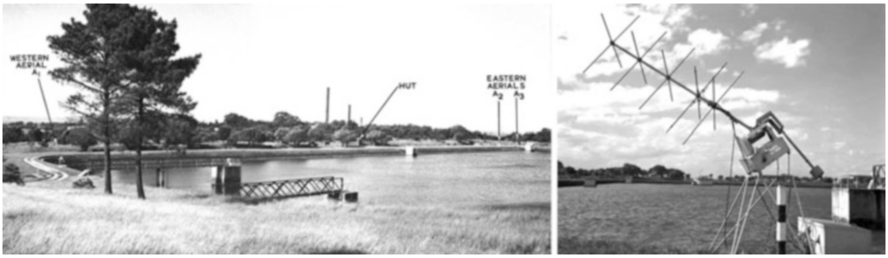

Fig. 3.2 Potts Hill field station and the swept-lobe interferometer used by Mills for observations of Cygnus A. The *left figure* shows the location of the three aerials of the swept-lobe interferometer and the associated receiver hut. The view is looking to the northeast. The *right figure* is a close-up view of the western Yagi aerial (Courtesy of the CSIRO Radio Astronomy Image Archive, 2313 and 2217; image date 28 July 1950)

> (simple Yagis). If I had been a trained astronomer, no doubt I would have chosen the H-line project, but I was intrigued by the mystery surrounding the “discrete sources” [the radio sources associated with radio galaxies and Milky Way nebulae] and had no hesitation in making this choice.[3]

Over a period of 8 months, from May to December 1949, Bernie, with the young English engineer Aidan Thomas, used the 97 MHz swept-lobe interferometer (see Fig. 3.2) located at the Potts Hill field station to determine the astronomical position of the strong discrete radio source Cygnus A:

> Eventually we determined a position with probable errors of some 2 min of arc.[4] A photograph of the general area of the Cygnus source had been sent to Bolton by Rudolph Minkowski and on the photograph, after much trouble, we found a small nebulous object within our positional uncertainties. We were confident that this was the source and that it was a Galactic nebulosity because of its location so close to the Galactic plane. However, before publishing, I wrote to Minkowski to seek his interpretation, naturally expecting that he would confirm our identification.

To Bernie’s great disappointment, Minkowski did not accept their identification. Although the Cygnus A source only rose some 16° above the horizon, they had managed to get their positional error down to 1.1 arcmin in right ascension and 3 arcmin of declination. Minkowski suggested, however, that this uncertainty was still too large to provide a definitive identification. Subsequently, Smith (1951, 1952) provided an updated position estimate with an error of 0.2 arcmin of declination and with this Baade and Minkowski (1954) confirmed the identification with a faint galaxy. This faint galaxy was the object originally proposed by Mills

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[3] Unsourced quotations are from Bernie Mills’s autobiographical notes, held by the University of Sydney Archives.

[4] The first identifications of radio sources with optical objects required an accuracy of about 1 arcmin.

and Thomas[5] (1951). The whole episode marked the beginning of Bernie's development of a "healthy scepticism toward authoritative pronouncements and the confidence to rely on my own judgment".

Badgerys Creek

With the limited sensitivity of the swept-lobe interferometer, only the strongest discrete sources could be detected. Spurred on by his curiosity, Bernie decided to build a new interferometer and continue his investigations. The increasing levels of radio interference at Potts Hill and the need for longer baselines required a new site, which he found at Badgerys Creek, a CSIRO cattle research station some 30 km to the west of Potts Hill.

A key feature of this new interferometer was that Bernie independently developed a phase-switching technique[6] essentially the same as that developed earlier by Martin Ryle, the leader of the radio astronomy team at Cambridge. One of the main issues he had been dealing with was that the relatively low sensitivity of the interferometer meant that it required long periods of integration. Thus, the instrumental response had to remain stable over this period, a problem solved by the phase switch. While exploring a solution to overcome this problem, Mills recalled:

> I had begun to look for a better alternative when I received some unintended assistance from Cambridge. News came through the grapevine that a revolutionary system had been introduced there but it was all very hush–hush and no details were known; it was believed that it involved a modulation of the interference pattern. This seemed to be just what was needed. A little thought suggested modulation by interchanging maxima and minima on the interference pattern by switching phase and using a synchronous detector, as in the Dicke system.[7] The necessary equipment was built, and it worked very well. Later I found that this was precisely the system used at Cambridge, the only difference being their use of a hardware switch in the antenna feed lines whereas I had used an electronic switch following the preamplifier.

Pawsey (1951) ensured that Mills acknowledged Ryle's priority in development of the phase switch even though no technical details had been provided to the Radiophysics group. The interesting development in Bernie's phase switch was that he used an electronic phase reversal switch after the preamplifiers. This scheme meant that a broader bandwidth implementation was possible.[8] This modification would be necessary for the conceptual leap to the development of the cross array.

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[5] For a full discussion of the identification of Cygnus A, see Sullivan, W. T. 2009. *Cosmic noise: a history of early radio astronomy,* Cambridge, Cambridge University Press pg 335.

[6] A technique to move the response pattern of the interferometer back and forth over a limited region of the sky; with this scheme, the long-term instrumental instabilities could be partly eliminated.

[7] In 1946, Robert Dicke of Princeton University developed an eponymous switching system for the detection of weak radio astronomy sources at microwave frequencies.

[8] The increased bandwidth leads to an increased sensitivity.

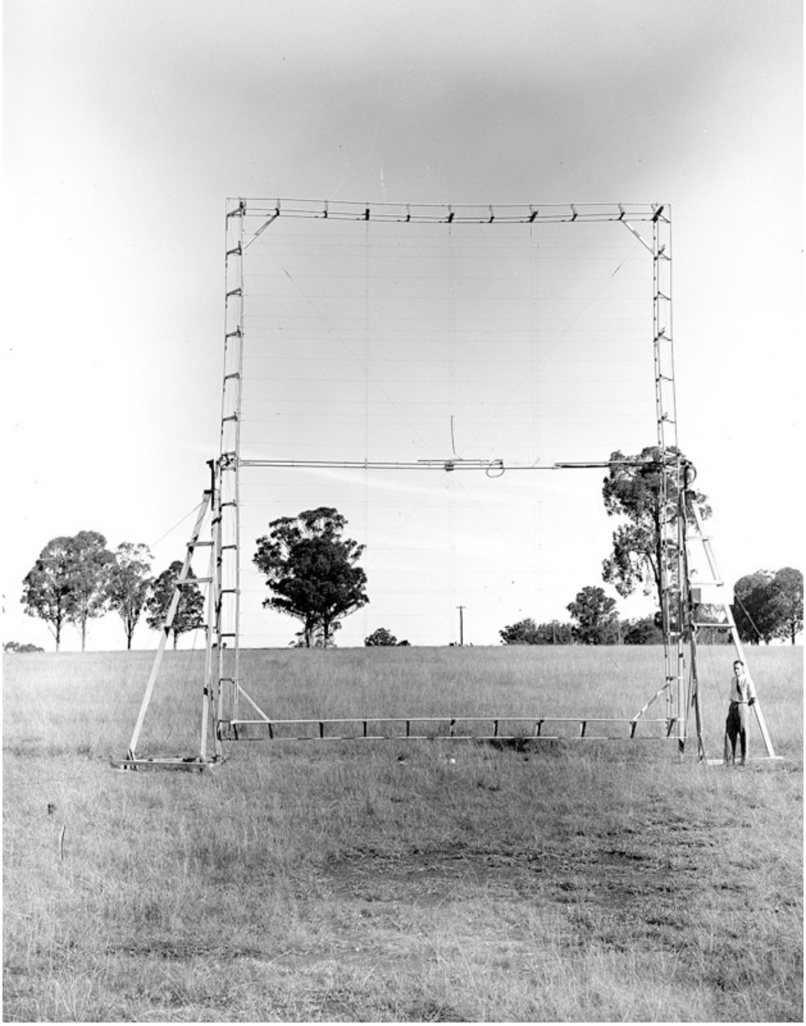

Fig. 3.3 One of the three broadside antennas of the 101 MHz interferometer at the Badgerys Creek field station (Courtesy of CSIRO Radio Astronomy Image Archive B2095-1 Image Date: 9 May 1950)

From February to December 1950, Bernie's team conducted a survey of the sky from +50° to −90° in declination using the new three-element interferometer (see Figs. 3.3 and 3.4). They observed at 101 MHz on an east-west baseline with two spacings of 270 and 60 m and identified 77 discrete sources. Bernie noted that many of the sources they observed were of an extended, rather than

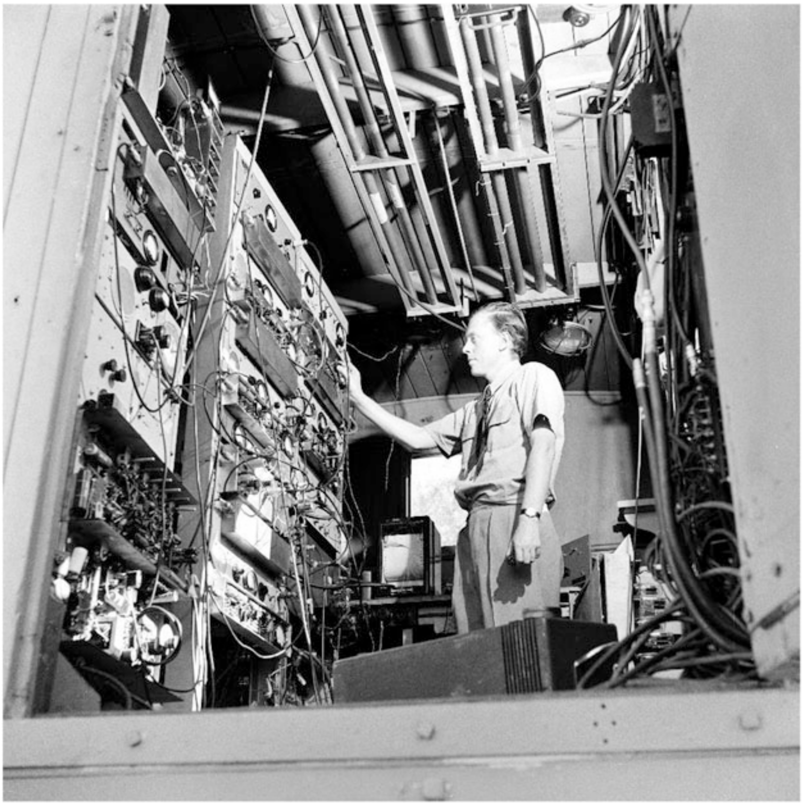

Fig. 3.4 Mills inside of the receiver hut for the 101 MHz three-element broadside array interferometer at Badgerys Creek in June 1952 (CSIRO Radio Astronomy Historical Photographic Archives B2774-1)

point source,[9] nature. He also noted that many of the stronger sources were concentrated along the Galactic plane and therefore actually fell into two major classes: Class I were Galactic, and Class II were isotopically distributed [evenly spaced] over the sky. Mills postulated that these sources could be either associated with "radio stars" within the Milky Way or could be extragalactic sources.

In reaching his conclusions, Bernie also used the comparison of the source counts Log (N) versus flux density Log (S) (plotted as the number of sources with flux density S or greater) to show that the Class II sources had a slope of -1.5, consistent with an isotropic (evenly distributed) distribution over the sky,

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[9] The extended sources were observed to be larger than 1° on the sky, while the compact sources were smaller than 1°.

while the Class I sources had a slope of −0.75, consistent with the non-homogeneous (sources concentrated towards the plane of the Milky Way) Galactic distribution. In conducting his analysis, he also pointed out some of the shortcomings of earlier attempts by Ryle (1950) to understand the distribution of radio emission. In a later section, we will elaborate on the controversy with Cambridge.

Bernie next conducted a more detailed investigation of six of the stronger discrete sources (Mills, 1952c) to determine accurate position estimates. To do this, he needed to extend the maximum baseline of his interferometer to 10 km. To achieve this, he developed a radio link, transmitting both the signal and local oscillator frequencies to preserve the phase of the signal when reconstituting the signal at the receiving link (see Fig. 3.5).[10] This experiment was the first time this technique had been used in radio astronomy; the scheme was quickly adopted by the Jodrell Bank group, who were also exploring the angular size of discrete sources using radio links.

With the 1952 International Union of Radio Science (URSI) conference (see Fig. 3.6) rapidly approaching, and with both the Jodrell Bank and Cambridge groups also studying the nature of the discrete sources, Mills decided to concentrate on resolving the sources Cygnus A, Taurus A, Virgo A and Centaurus A and trying two other baseline orientations to help discover the angular extent of the sources. Completing these observations just in time for the URSI meeting, Bernie found that the angular radio sizes were comparable to the optical sizes of the nebulae themselves, and this provided strong evidence that the discrete sources were largely, if not entirely, nebulae of both Galactic and extragalactic origin (Mills, 1952a, b). The results were presented together with results from Jodrell Bank and Cambridge during URSI 1952 and later published in *Nature* (Hanbury-Brown, Jennison, & Das Gupta, 1952; Smith, 1952). Unfortunately, as Sullivan (1982) has noted, in his rush to complete the observations, Bernie lacked the critical spacing between 1 and 5 km that would have allowed him to detect for the first time the double structure of Cygnus A and that would later prove key to understanding the nature of these sources (Jennison & Das Gupta, 1953). This honour would go to the Jodrell Bank team, who also used a radio-link interferometer but with a large sample of spacings that allowed them to detect the double-lobe nature of the source.

However, in a more detailed follow-up paper in *Nature*, Mills produced “radio pictures” for comparison with the optical nebulae counterparts. This was the first time greyscale representation of the brightness distribution had been used in radio astronomy.

These first years of the 1950s marked the beginning of a revolutionary period in understanding the nature of the discrete sources and would set Bernie on a path of

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[10] The radio link was used to transmit (1) the signals back to the central receiver and (2) the control signals from the home station to the distant aerial.

Fig. 3.5 The portable twin Yagi aerial system used by Mills in conjunction with a radio link to the 101 MHz broadside arrays to provide a variable interferometer spacing that allowed him to investigate the radio brightness distributions of the sources Centaurus A, Cygnus A, Taurus A and Virgo A. This photograph was taken in June 1952 and Mills presented his preliminary results during the 1952 URSI meeting (CSIRO Radio Astronomy Historical Photographic Archives B2786-6)

challenging the assertions, particularly from Martin Ryle's group in Cambridge, on the nature of "radio stars" and the distribution of the discrete sources and their cosmological implications.

Fig. 3.6 Some of the attendees at the 1952 URSI Meeting in Sydney. From *left* to *right*: *First row*: J.G. Bolton, O.B. Slee, M. Laffineur (France), A.G. Little, R. Payne-Scott, R. Hanbury-Brown (England), C.A. Shain, C.F. Smerd, J.L. Steinberg (France), B.Y. Mills, J.P. Wild, F.G. Smith (England), W.N. Christiansen. *Second row*: C.A. Muller (Netherlands), F.J. Kerr, H.I. Ewen (USA), J.V. Hindman, J.P. Hagen (USA), C.S. Higgins. *Third row*: L.W. Davies, E.R. Hill, J.H. Piddington (Courtesy of ATNF Historical Photographic Archive: 2842-43 Image Date: 8 August 1952)

The Idea for a Cross

Using the new phase-switched interferometer at Badgerys Creek, Bernie soon discovered another major problem in using spaced interferometers for survey work: many of the sources resolved at the short spacing bore no resemblance to those detected at the longer spacing. He had determined that this was most likely caused by the sources being extended in nature rather than being point sources.

Bernie believed that sensitivity was not the issue for the source survey work at metre wavelengths; rather, high resolution was the key requirement. As he stated (Mills, 2006):

> By then, I knew that collecting area was relatively unimportant; the important thing was a large overall size to give high resolution. As a filled array seemed wasteful, I first looked at various passive configurations such as crosses and rings, but these all suffered from high

> side-lobe levels. Suddenly it occurred to me that by combining the phase-switch, which I had used on the interferometer, with a crossed array, the side-lobe problem would be substantially reduced.[11]

The extent of Bernie's physical grasp of how things work is well illustrated by his commentary on the evolution of the cross concept[12]:

> A solution occurred to me after discussing the imaging problem with Christiansen who was using two grating arrays along the sides of a reservoir to produce maps of the sun by the first application of earth rotation synthesis. However, fast imaging was really needed because of the variable solar emission, quite apart from the inconvenience of carrying out Fourier transforms[13] when no computer was available. With my thoughts concentrated on linear arrays, I soon realized that a solution to both our needs was an antenna in the form of a symmetrical cross, with the outputs of the arms combined through a phase reversing switch as then used in my interferometer systems. Only the signals received in the overlapping area of the fan beams would produce a modulated signal that could be picked out with a phase-sensitive detector to produce a simple pencil beam response, or, in the case of grating arrays, an array of pencil beams. This process effectively multiplied the two antenna responses.

This conceptual breakthrough goes back to Bernie's earlier experiences with the phase-switched interferometer and was precisely the technique needed to produce the principal beam response [the position of maximum sensitivity of the instrument] of the cross.

While Pawsey quickly embraced the idea of constructing a cross, others (including Bowen) were more sceptical, and it was therefore determined that a proof of concept should be constructed. Bernie was joined by the Technical Officer Alec Little at the start of what would turn out to be a 32-year partnership. They built the prototype at Potts Hill using chicken wire and wooden posts, with the arms of the cross 36 m in length (see Fig. 3.7). The combined response of the arms produced an 8-degree pencil beam. The prototype not only successfully proved the concept was viable, but the prototype also resulted in the first radio-continuum detection of the Large Magellanic Cloud (Mills & Little, 1953).

The cross-type concept proved versatile in radio astronomy and later inspired new techniques in radar and, more widely, multi-beam sonar designs. The first of these was patented in 1964 by SeaBeam Instruments – at the time the Harris Anti-Submarine Warfare Division of General Instrument Corporation – and used by the US Navy and later the Royal Australian Navy (L-3 Communications Seabeam Instruments, 2000).

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[11] The reduction in side-lobe level was due to the filled geometry of both arms of the cross.

[12] See Appendix A.

[13] The mathematical operation to apply to the observational data in order to produce an image of the radio sky

Fig. 3.7 A close-up view of the prototype Mills Cross at the Potts Hill field station. The prototype cross operated at 97 MHz with a beamwidth of 8°. Each arm of the cross was 36 m in length (Courtesy of CSIRO Radio Astronomy Image Archive: B3064-3 Image Date: 21 April 1953)

Fleurs and the Mills Cross

Following the success of the prototype cross at Potts Hill, Radiophysics allocated the necessary resources to build a full-scale instrument. A new site was needed, as both Potts Hill and Badgerys Creek had insufficient flat ground for such an instrument. A disused WWII airstrip close to Badgerys Creek provided the ideal location, and in 1953, the Fleurs field station was established.

The new cross was constructed during 1953–1954, largely by Alec Little, as Bernie was on a 6-month study tour of the USA:

> During all this activity, I received an invitation to spend 6 months in the United States visiting the California Institute of Technology and the Department of Terrestrial Magnetism [Carnegie Institute of Washington], which was developing a program in radio astronomy. The invitation came at an awkward time, but to decline was unthinkable, and I had no qualms about leaving the supervision of construction in the capable hands of Alec Little. This visit was well worthwhile as the few months spent at Cal Tech marked a turning point in my grasp of astronomy and astrophysics. Discussions with some of the leading astronomers and astrophysicists of the day (particularly the iconoclastic Fritz Zwicky), attendance at colloquia, and even a postgraduate course on stellar structure all helped to fill in

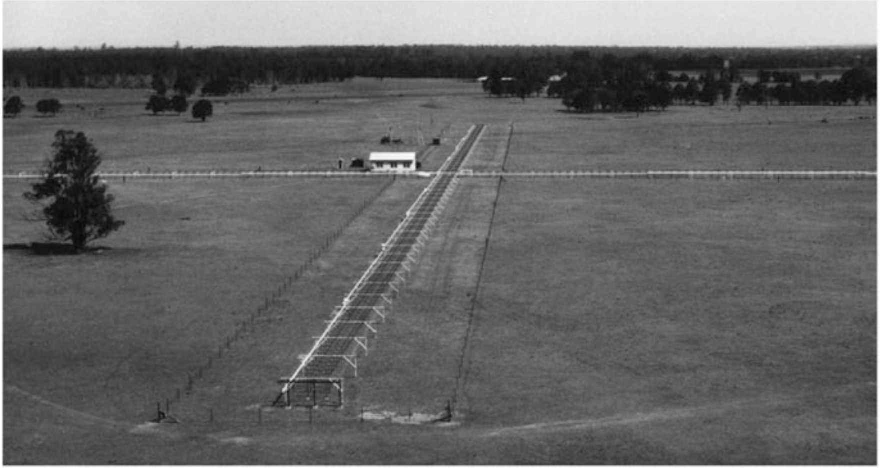

Fig. 3.8 The Mills Cross at the Fleurs field station looking south along the north-south arm. The telescope operated at 85.5 MHz with a beamwidth of 48 arcmin. Each arm of the cross was 450 m in length (Courtesy of CSIRO Radio Astronomy Image Archive: 3476-3 Image Date: 25 October 1954)

> some of the numerous gaps in the knowledge I had managed to acquire. I returned home in early 1954 with my mind full of plans for observational programs.

The new cross operated at 85.5 MHz, with each of the north-south and east-west arms 450 m in length, giving a beamwidth of 48 arcmin (see Figs. 3.8, 3.9, 3.10, 3.11, 3.12 and 3.13). Observations began in 1954, and the cross was immediately successful (Mills, 1955, 1956), with studies of Galactic sources, the Magellanic Clouds and other external galaxies (see Figs. 3.14, 3.15 and 3.16).

Controversy with Cambridge

Soon after beginning a southern sky survey with Bruce Slee (see Fig. 3.13) using the new cross, Bernie received a letter from Fred Hoyle[14] asking his views on the validity of the data and cosmological claims being made by Ryle's group

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[14] Fred Hoyle (1915–2001), prominent UK astrophysicist and cosmologist, primarily known for the theory of stellar nucleosynthesis. One of the founders of the Steady State theory of the universe along with Hermann Bondi and Thomas Gold. The Steady State theory is an alternative to the Big Bang model of the evolution of the universe. In the Steady State theory, the density of matter in the expanding universe remains unchanged due to a continuous creation of matter. The modern Big Bang theory is one in which the universe has a finite age and has evolved over time through cooling, expansion, and the formation of structures through gravitational collapse. The Big Bang is the accepted model of the universe in the twenty-first century.

Fig. 3.9 Construction of the east-west arm of the 85.5 MHz Mills Cross at Fleurs field station in October 1953. The view is looking west with the base of the array arm mesh "chicken wire" reflector support frame in place. The receiver hut is visible in the background (CSIRO Radio Astronomy Historical Photographic Archives 3174-25)

based on their 2C survey (Shakeshaft, Ryle, Baldwin, Elsmore, & Thomson, 1955). By this time, Ryle had reversed his earlier views that "radio stars" were the source of the discrete radiation and now favoured an extragalactic origin. Based on the newly completed Second Cambridge (2C) survey, the Cambridge team found that examining the plot of the log of the number of sources (N) brighter than the log of a given flux density (S) produced a slope steeper than -1.5 based on a very large number of faint sources. A slope of -1.5 would have been consistent with a Euclidean universe (local geometry is flat) and the Steady State theory proposed by Hoyle. In his 1955 Halley lecture at Oxford, Ryle had audaciously concluded that this effectively ruled out the Steady State cosmological model supported by Hoyle (Ryle, 1955; Ryle & Scheuer, 1955).

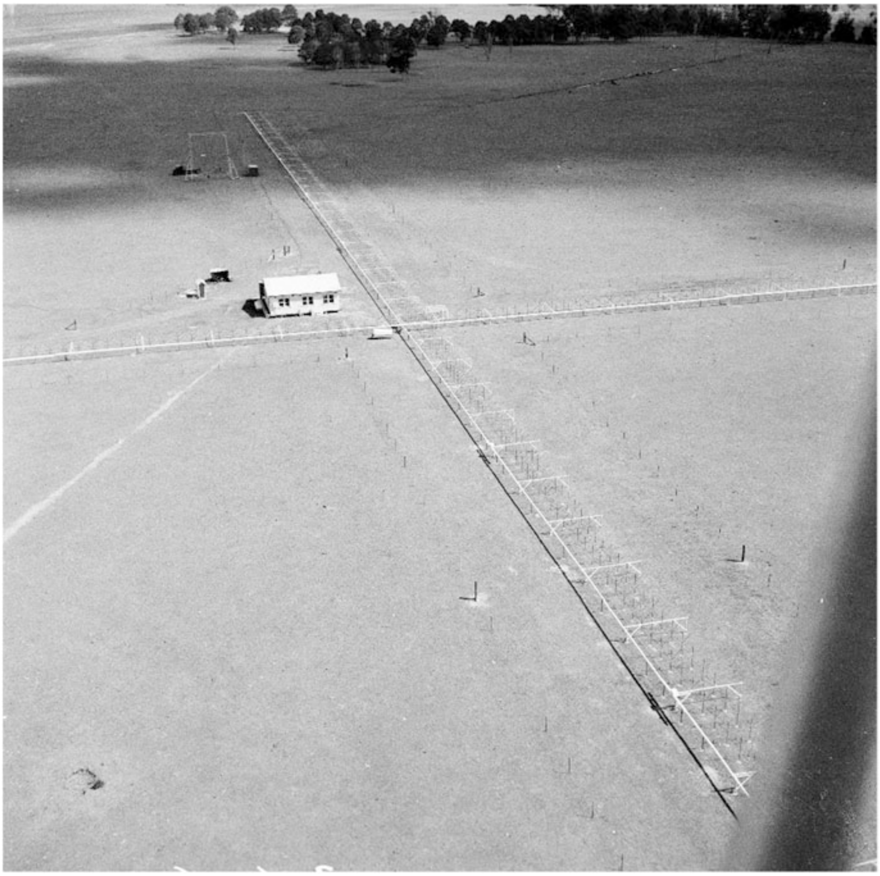

Fig. 3.10 An aerial view of the completed Mills Cross array at Fleurs field station in October 1954. The view is looking south along the north-south arm. One element of the 101 MHz broadside array from Fig. 3.3 is visible behind the receiver hut. The fence around the array is to keep farm animals out (CSIRO Radio Astronomy Historical Photographic Archives 3476-1)

This pronouncement marked the entry of radio astronomy into the field of cosmology.[15]

Bernie recalled in detail the events that unfolded around the discord between the two surveys and the circumstances are discussed extensively by Edge and Mulkay (1976) and Kragh (1996). While initially there was regular communication with Cambridge about the discrepancies that were already apparent between the surveys, the relationship quickly deteriorated as Ryle refused to accept that there were

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[15] For a uniform distribution of sources in the universe as predicted in a Steady State universe, the slope was predicted to be -1.5; for an evolving universe (Big Bang), the slope was predicted to be somewhat more negative due to the changing properties of the sources over the lifetime of the universe (higher density of radio sources when the universe was younger).

Fig. 3.11 L-R Unknown, Alex Shain, Bruce Slee, Bernie Mills, Kevin Sheridan, Alec Little and Henry Rishbeth at Fleurs field station. Rishbeth had a joint CSIRO and UK fellowship in 1955–1957 working with Pawsey in Sydney. He carried out observations with the Mills Cross (3.7 m) and the Shain Cross (7.9 m). A major result was the discussion of the Vela-Puppis region of the galactic plane. After returning to the Cavendish Laboratory in 1957, he received a PhD in 1960. The remainder of his career he worked as an ionospheric physicist, ending as a professor at Southampton University (CSIRO Radio Astronomy Historical Photographic Archives B13097-1)

serious problems with the 2C survey. After it became clear that Ryle was ignoring the conclusions being reached in Sydney, Bernie decided to publish his group's preliminary survey results (see Fig. 3.17), including a formal criticism of the Cambridge survey, pointing out the flaws in technique, and that "deductions of cosmological interest derived from its analysis are without foundation". With the benefit of hindsight, it is clear that the 2C survey was severely "confusion" affected (the blending of several weak sources in the side-lobes of the interferometer, to give a response like one stronger source) and that Bernie's objections to drawing conclusions based on the discrete source counts was correct (Sullivan, 1990: 309). By late 1956, the observations for the Third Cambridge (3C) survey were largely complete, and their early analysis confirmed the criticism of gross confusion in the 2C catalogue, although the final results were not published until 1959 (Edge, Shakeshaft, McAdam, Baldwin, & Archer, 1959). Ryle knew by late 1957 [when the Mills and Slee paper was published (Mills & Slee, 1957)] that the results for 3C were not compatible with the Steady State model. However, he refused to withdraw his claims concerning the significance of the conflicting source counts. The debate between cosmological models would continue for many more years until this issue

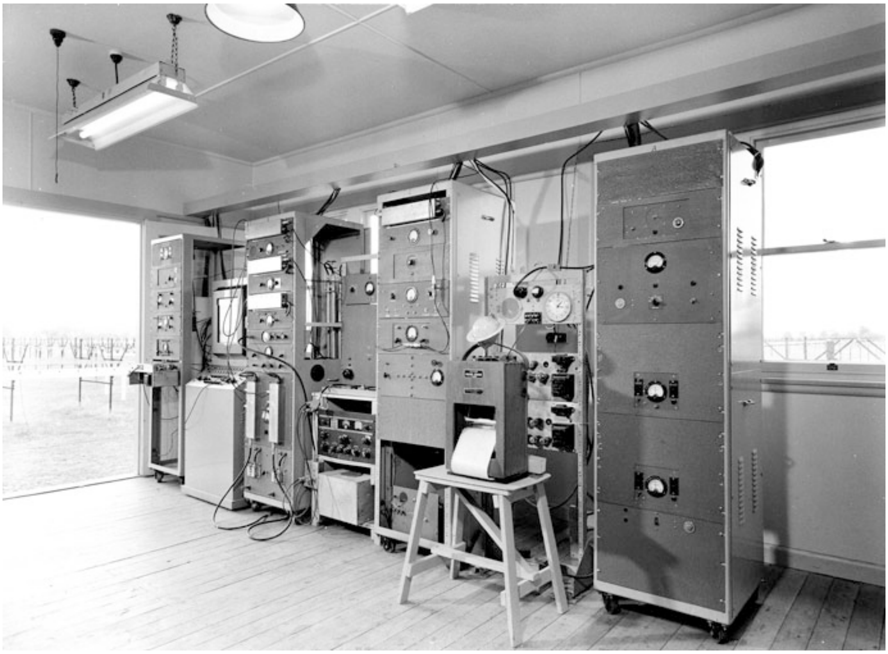

Fig. 3.12 Equipment inside the receiver hut of the 85.5 MHz Mills Cross (CSIRO Radio Astronomy Historical Photographic Archives B3454-4)

was largely settled by the serendipitous discovery of the cosmic microwave background by Penzias and Wilson in 1965.

While the controversy continued, the Fleurs Mills Cross proved itself to be an excellent survey instrument at metre wavelengths and especially suited for the study of our own Galaxy, allowing the different components of Galactic radiation to be identified. The full survey, known as MSH, was completed in 1957 and published in three separate papers (Mills, Slee, & Hill, 1958, 1960, 1961). The survey at 85.5 MHz, with a 48 arcmin beam, covered most of the southern sky between declinations of +10° and −80°, cataloguing 2270 radio sources down to around 7 Jy. The MSH survey itself, however, was not immune from the effects of confusion, with some of the extended sources later proving to be blends of separate sources.

In a further attempt to better understand the nature of the extragalactic discrete sources, Bernie endeavoured to derive a luminosity function and to more accurately measure their angular extent (Goddard, Watkinson, & Mills, 1960). Returning to the idea of the radio-link interferometer, the team extended the baseline by combining the cross with an aerial 10 km distant. In this configuration, it was possible to obtain resolution as high as 10 arcsec at 85.5 MHz. However, in both cases, the findings were inconclusive, and a more detailed understanding would have to wait

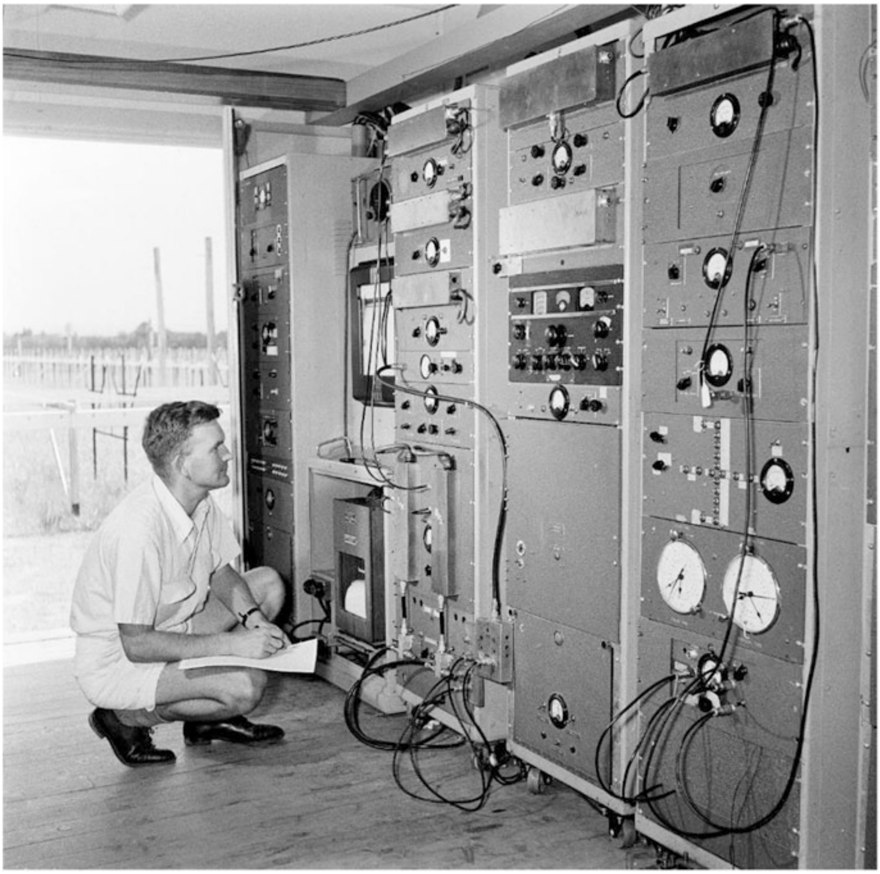

Fig. 3.13 Bruce Slee (1924–2016) examining one of the paper chart recorders of the Mills Cross in November 1955 (CSIRO Radio Astronomy Historical Photographic Archives B3868-10)

for the discovery of quasars (Mills, 1960). Quasars are barely detectable at 85 MHz due to their flat and inverted radio spectra, and higher frequency surveys were needed to begin to understand the nature of these sources.

In 1959, Bernie was awarded the degree of Doctor of Science in Engineering for a thesis covering the development of the 85.5 MHz cross and its observations.

With the MSH Survey now complete, Bernie travelled for the first time to Europe to attend the Paris Symposium on Radio Astronomy and then the 1958 International Astronomical Union General Assembly in Moscow where he presented many of the results from the observations covering Galactic structure and the discrete sources. This chance to meet and present his own research to the broader astronomical community marked the end of his successful transition from engineer to astronomer.

Fig. 3.14 A close-up view along an arm of the Mills Cross. To the right, a parallel arm of the Chris Cross is visible (CSIRO Radio Astronomy Historical Photographic Archives P12205-7)

Fig. 3.15 Bernie Mills with Grote Reber standing next to the Mills Cross at Fleurs in the late 1950s (CSIRO Radio Astronomy Historical Photographic Archives P13871-6)

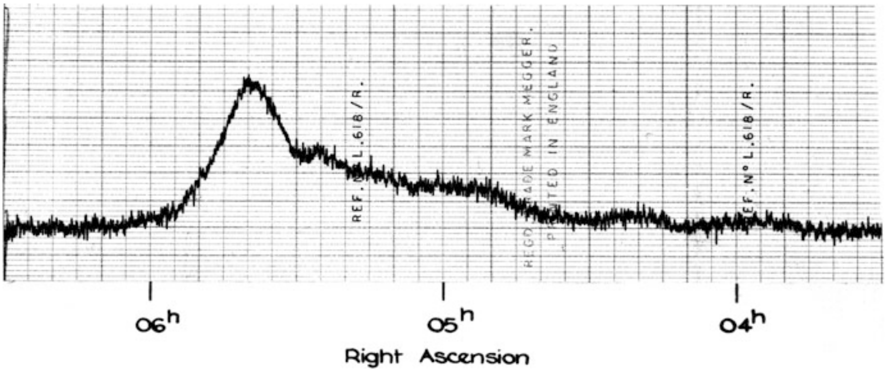

Fig. 3.16 An example chart recording from the Mills Cross showing the 85.5 MHz radio emission obtained from a transit scan at the declination of the Large Magellanic Cloud (CSIRO Radio Astronomy Historical Photographic Archives B3598)

The One Mile Cross

Around this time in the 1950s, funding was obtained for the design and development of the Giant Radio Telescope (GRT) – the Parkes 64 m radio telescope; support for other projects languished. Mills and Christiansen were commissioned by Bowen to find a new site in central New South Wales, Australia. As they drove the peg to mark the approximate position of the new GRT on a farm near Parkes (see Fig. 3.18), both likely realised there was no future within Radiophysics for their types of cross and array radio telescopes in cosmic research[16]. All remaining resources available to the Radiophysics Division were reserved for Paul Wild's Culgoora Radioheliograph for solar research, and there was nothing left for a large cross (Bowen, 1981). Bernie's criticism of the GRT project was not about the scientific usefulness of the telescope itself, which proved extremely well suited to high frequencies and spectral analysis; rather, it was that Radiophysics would effectively be abandoning high-resolution, low-frequency cosmic research.

Even though Pawsey was a major proponent of a new Mills Cross with higher resolution and sensitivity, calling it "the Super-Cross" and noting that Mills's past work "has been outstanding, his contribution has probably been the greatest single

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[16] As an interesting aside, Bowen would later recreate the event of driving in the first peg at the Parkes site at another location some distance to the south of the telescope, effectively editing Mills and Christiansen out of his own history (see Fig. 3.18). In 1971, Frank Kerr told W.T. Sullivan about the staged event: "… Taffy Bowen went up to the site… with McCready and he got McCready to take a picture of him driving the post in. And that picture has been published in various propaganda journals". In addition, Paul Jelbart, a nearby neighbour who lived on an adjacent property at Parkes, witnessed the recreation in September 1961, only a month before the official opening. The site of the recreation is some 200 m south of the 64 m telescope (John Sarkissian, private communication).

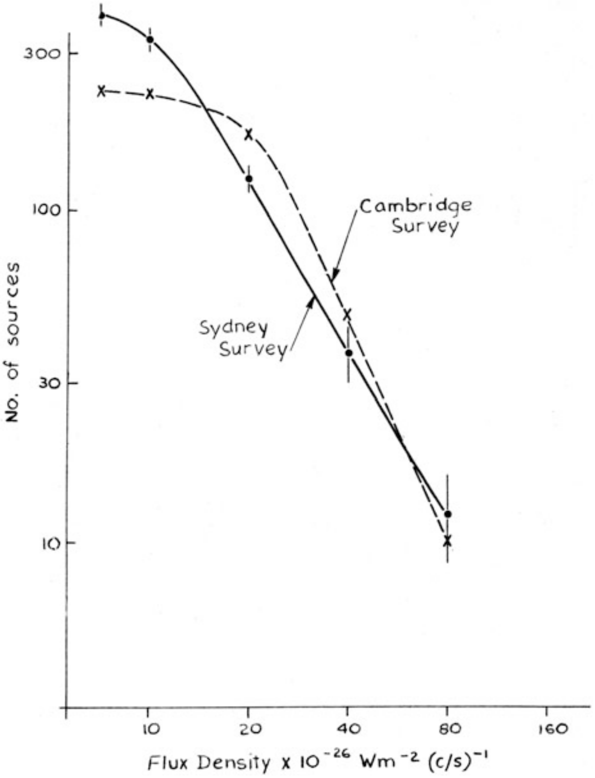

Fig. 3.17 Plots of the number of radio sources at a given flux density (strength of emission) comparing the different slopes of the Cambridge and Sydney survey. The Cambridge (2C) survey showed a slope steeper than −1.5 which implied a non-uniform distribution of sources. Ryle deduced that this indicated cosmological evolution rather than a Steady State model. The Sydney survey slope was much closer to −1.5, and Mills questioned the accuracy of the 2C survey and hence the basis for the cosmological claims. As it turned out, Mills was correct to question the accuracy of the data in the 2C survey which was flawed; however, Ryle's conclusion proved correct in spite of the inaccuracy of the 2C results (CSIRO Radio Astronomy Historical Photographic Archives B5057-2)

factor in giving Australian radio astronomy the high prestige it now enjoys" (Pawsey, 1960), the planning and commitment to the GRT by Radiophysics triggered major career changes for Bernie. He investigated chairs of Electrical Engineering at Adelaide, Melbourne and Sydney, but these did not offer the financial support to build his large cross-type telescope. He finally found it, not in Engineering, but in Physics, at the University of Sydney.

Start of Molonglo Planning

Harry Messel, Professor of Physics at the University of Sydney in September 1952, established the Nuclear Research Foundation (the first such foundation in the British Commonwealth which later changed its name to the Science Foundation

Fig. 3.18 *Top* The original record of Mills hammering in a survey stake at the Parkes site with Christiansen looking on at the far *right* taken in March 1958. The original landowner, Austie Helm, is standing in the background. The person holding the stake is unknown (Courtesy of the Mills family archive). *Bottom* Bowen's recreation of the event watched by Lindsay McCready taken on 29 September 1961 just prior to the opening of the 64 m Parkes Radio Telescope when the telescope had already been completed (Courtesy of CSIRO Radio Astronomy Image Archive B6586)

for Physics) to "…promote, foster, develop and assist …research with grants from … fees, donations and the like" (McAdam, 2008). Between November 1959 and November 1961, Messel recruited new professors in theoretical, thermonuclear (plasma) and high-energy nuclear (cosmic rays) physics, as well as electronic computing. When Robert Hanbury-Brown in Manchester in the UK sought funds and a site for his optical intensity interferometer, Messel began an astronomy group and invited Hanbury-Brown to Australia to build at a site near Narrabri in northern NSW. Messel also had funds for a complementary photometric telescope and sent Colin Gum to Europe to examine optical designs. Unfortunately, in April 1960, Gum died in a skiing accident in Switzerland, and the telescope project never went ahead. Messel then contacted Mills, approved the concept of a large cross-type radio telescope and offered him seed money sufficient to build a 408 MHz Cross with arms about 400 m long.

In June 1960, at age 40, Bernie started a new career at the University of Sydney where he was to remain for the next 25 years. His initial plans were dependent on funding. He commented:

> From the beginning there seemed to be few problems in constructing a cross within the available budget of $200,000 which would be able to survey the sky at metre wavelengths with a sensitivity and resolution at least equal to that anticipated for the Parkes radio telescope operating at its optimum wavelength. But why stop there?

Any further funds would mean longer arms replicating a flexible modular design. The challenge was to find the additional financial support for a larger cross.

Through some of his many overseas contacts, Messel learned that the National Science Foundation (NSF) was willing to make grants outside of the USA. Mills quickly wrote a proposal for his ambitious 1-mile cross-type radio telescope. In support of this, he provided results from his 85.5 MHz Fleurs Mills Cross survey and made precise predictions of possible observing programmes, the number of fainter sources expected, their confusion levels and the sensitivity required of the telescope.

The project then met opposition from Bowen, who advised against any grant, stating that a small university group could never manage such a large project. He had a largely vested interest in keeping funding for radio astronomy only to his group at CSIRO. When the NSF sent Geoffrey Keller, who was the Project Director for Astronomy, to Australia to investigate, Messel advised him to go to Canberra and talk to Bart Bok, the Director of Mount Stromlo Observatory. Bok was considered impartial and not directly involved in radio astronomy. The visit reassured the NSF, and in 1962, they approved the grant. The initial funding of US$746,000 was followed by a further US$107,500 in 1964 and allowed the project to go ahead with its planned mile-long arms. In his first published description of the project, Mills wrote: "This is a greatly enlarged version of the original 'Mills Cross' put into operation by the CSIRO in 1954 …the beamwidth would be about 2.8 arcmin and the sensitivity adequate to detect more than a million radio sources".

Meanwhile Messel negotiated the purchase of a site for the new cross in a wide flat valley near Canberra. This was one of the sites that had been investigated for the GRT but which had been rejected in favour of Parkes. The height of the GRT would have put it in line of sight over hills to the transmitters on Black Mountain in Canberra, but the cylindrical reflectors of the Cross were lower and remained shielded. Thus, in the

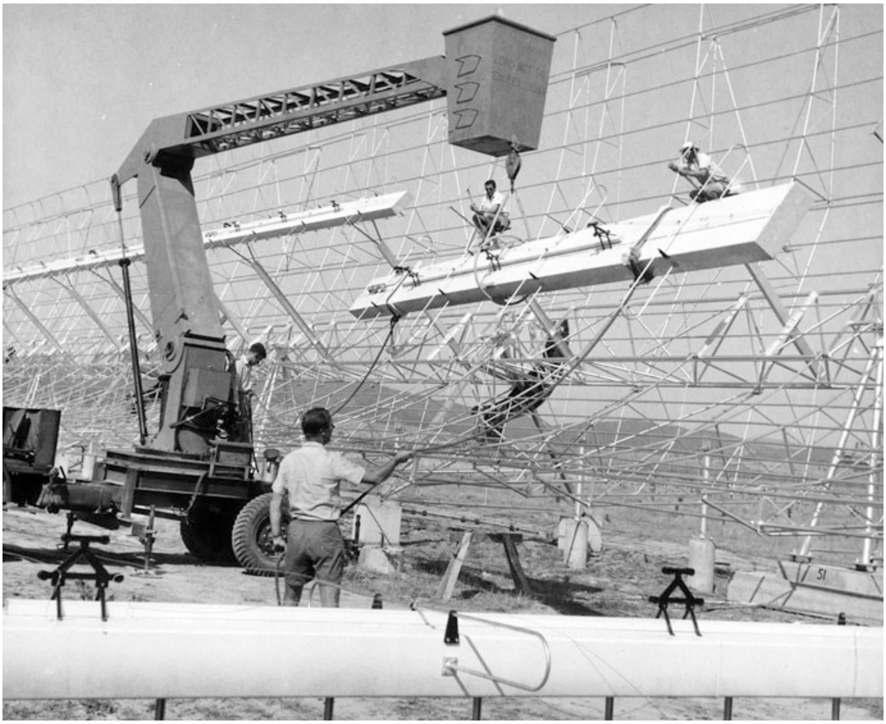

Fig. 3.19 The construction of the east-west arm of the Molonglo Cross (Courtesy of the University of Sydney Archives)

Parish of Molonglo on a branch of the Molonglo River, construction of the Molonglo Radio Observatory commenced in 1961 (see Figs. 3.19 and 3.20).

Bernie brought two valued colleagues from Radiophysics, Alec Little and Arthur Watkinson, and recruited three young radio astronomers from the UK, Bruce McAdam and Tony Turtle from Cambridge, and Michael Large from Manchester, into his group. This small university group built the Cross over the next 6 years but did so in cooperation with many university and industrial colleagues. Many years later, Mills was to reminisce: “I found myself manager of a big engineering project. It was not an enjoyable job but there was no one else to do it, and I was much helped by my engineering contacts, stretching back in some cases to student days”.

From the start, there was a major partnership with Chris Christiansen, in the School of Electrical Engineering, who took responsibility for the receiving system. The cooperation was made formal with the formation of the Radio Astronomy Centre in the University of Sydney (Messel, 1960). Bob Frater, one of the present authors, left industry (AWA, OTC and then Ducon) to join the Electrical Engineering Department in 1961 specifically to work on the electronic design of the Molonglo Cross using the (then new) transistor technology. Frater (2005) later commented: “I jumped at the opportunity. Bernie had in mind an instrument where the technical demands stretched significantly beyond the technology of the time”.

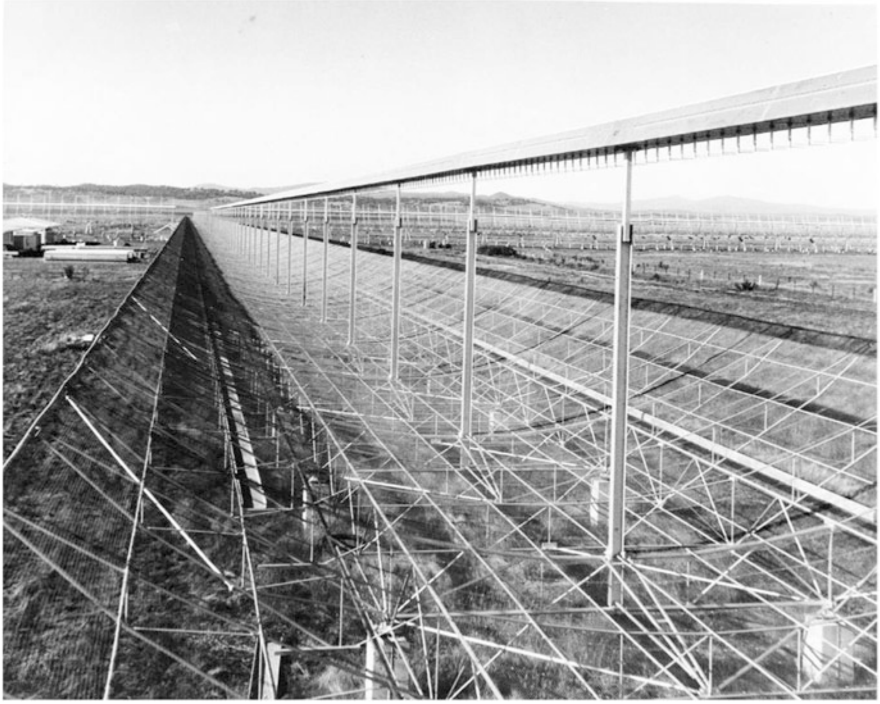

Fig. 3.20 The Mills "Super-Cross" under construction at Molonglo near Canberra in 1966. The view is looking east towards the centre of the array (CSIRO Radio Astronomy Historical Photographic Archives B8181-6)

The official opening ceremony for the Molonglo Observatory was held on 19 November 1965 and was attended by the Prime Minister of Australia, Sir Robert Menzies (see Fig. 3.21).

The full cross became operational in 1967, making measurements of the sky at 408 MHz (see Figs. 3.22, 3.23, and 3.24). Major research achievements using the new telescope included the Molonglo Reference Catalogue of 12,000 sources and numerous pulsar surveys completed during the 11-year operation. More than half the pulsars and supernova remnants known at the time were discovered at Molonglo, the most significant (see Fig. 3.25) being the Vela pulsar (Large, Vaughan, & Mills, 1968). The accurate position enabled the subsequent association with the Vela supernova remnant and the later optical detection of the pulsar using the Anglo Australian Telescope (Goss, Manchester, McAdam, & Frater, 1977; Wallace et al., 1977). The accurate Molonglo positions (typically 2–3 arcsec) enabled radio-optical identifications to be established on the basis of positional agreement alone, thereby providing a grid of southern hemisphere calibration sources[17] for both Molonglo

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[17] Radio sources with previously determined accurate positions on the sky, usually associated with known radio galaxies or quasars. Often these sources had well determined flux densities.

Fig. 3.21 Mills enjoying a moment with the Australian Prime Minister Sir Robert Menzies during the official opening ceremony for the Molonglo Observatory on 19 November 1965. The Head of the School of Physics at the University of Sydney, Professor Harry Messel, is on the far *right* (Courtesy of the University of Sydney Archives)

and Parkes. The Molonglo Cross made a complete survey of the southern sky, including the Galactic plane, which showed diffuse radio emission delineating the spiral arms of the Galaxy, as first seen in Bernie's early MSH survey, and an iconic image of the Galactic centre.

The Accumulation of Talent

Over the course of the development of the Molonglo Observatory, Bernie managed to attract an amazing array of talent to the project both directly and indirectly. This group was a testament, not only to Mills's reputation as an astronomer and engineer but also to his skill as a leader. Among the University of Sydney staff associated with Molonglo Observatory, 1960–1978, were:

From the School of Physics David Crawford, John Durdin, Richard Hunstead, Michael Large, Alec Little, Alan Le Marne, Hugh Murdoch, Bruce McAdam,

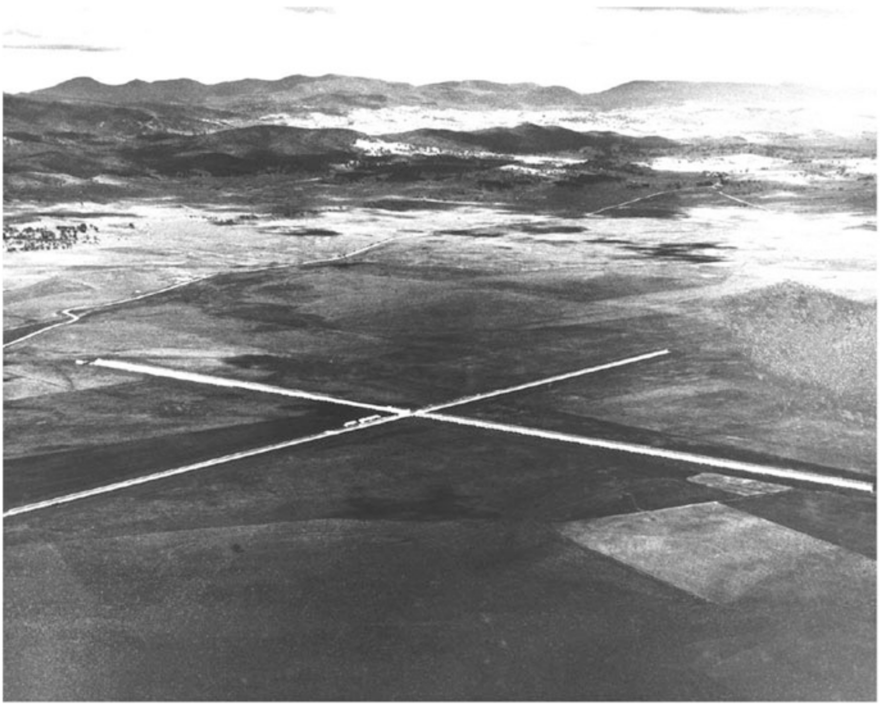

Fig. 3.22 An aerial view of the completed Molonglo Cross looking southeast. The observatory buildings visible near the centre of the cross are aligned along the north-south arm. The telescope operated at 408 MHz with a beamwidth of 2.8 arcmin. Each arm of the cross was 1.6 km in length (Courtesy of the University of Sydney Archives)

Tony Turtle and Arthur Watkinson with technical support from Terry Butcher, Grant Calhoun, John Horne, Jack Howes, Cornelius Kohlbrugge and Michael White.

From Electrical Engineering Ron Aitchison, Chris Christiansen, Bob Frater, Ian Lockhart and Cyril Murray.

The Molonglo Observatory Synthesis Telescope (MOST)

By the early 1970s, digital computers had achieved both the speed and reliability to take real-time control of a radio telescope. Bernie realised that if a fan beam tracked a field for 12 h, the rotation of the earth would move the beam through 180° on the sky and allow the synthesis of a pencil beam. He designed a synthesis telescope for 1420 MHz, and Alec Little developed a prototype feed for the east-west modules when they learned that CSIRO was planning the Australian Synthesis Telescope (later the Australia Telescope) for this and higher frequencies. Bernie then chose a

Fig. 3.23 The central section of the Molonglo Cross in 1967 with Libby Goss standing on the path leading to the Hut, taken a few months after Goss's first visit to Australia (Goss Collection)

Fig. 3.24 An aerial view of the inner section of the Molonglo Cross in 1969 (CSIRO Radio Astronomy Historical Photographic Archives N9117-8)

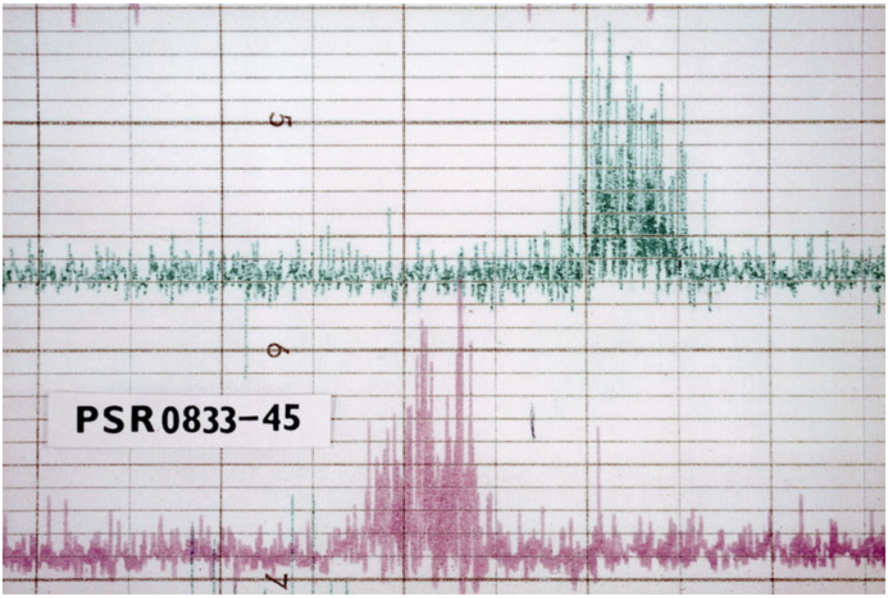

Fig. 3.25 A chart record of the short period Vela pulsar discovered with the Molonglo Cross operating at 408 MHz with a beamwidth of 2.8 arcmin by Large et al. (1968) (Courtesy of the University of Sydney Archive)

new frequency of 843 MHz, which is not a protected radio astronomy band but, with cooperation from the Australian Post Office, has been kept reasonably free of interference from nearby fixed and mobile radio phone transmitters.

In 1978, the group began converting the Molonglo Cross to the Molonglo Observatory Synthesis Telescope (MOST), and operations commenced only 3 years later. Bernie has emphasised the essential role of Alec Little in this conversion; Alec died in March 1985, aged 60, before the full potential of his work could be achieved. Bernie lost a valued colleague who had worked with him for 30 years.

The conversion of the Cross to the MOST reused the east and west arms and produced a powerful new telescope operating at 843 MHz that retained much of the original Cross infrastructure and electronics. This background was the predominant reason for choosing the new operating frequency, as it enabled reuse of the waveguides and local oscillator system. Mechanically, a slow tilt drive was added. The total length of the east and west arms together remained at 1.6 km (one mile) (see Fig. 3.26). The conversion of the feeds and construction of new receivers, digital delays and analogue beam formers to produce 128 contiguous fan beams took 3 years to complete (Robertson, 1991).

The first synthesis map of source 1733-565 was made on 15 July 1981 with 43 arcsec resolution over a 23 arcmin field. Switching beams across three adjacent centres increased the field to 70 arcmin, and detailed images of known sources up to 1° in size were observed for a decade.

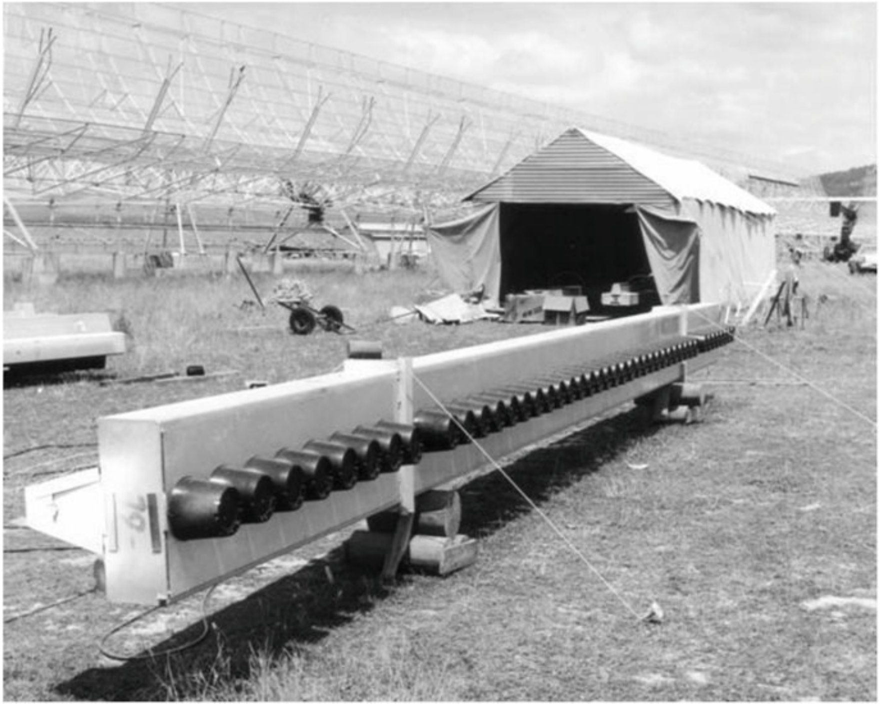

Fig. 3.26 The construction of MOST. The 408 MHz dipoles were replaced with 7744 ring elements that were phased by differential rotation under computer control to track a field for 12 h. Black flower pots were a novel way of protecting the ring antennas. In the MOST configuration, only the east-west arm (visible in the background) of the original cross was used (Courtesy of the University of Sydney Archives)

The last major observation program overseen by Bernie at Molonglo was a study of supernova remnants in the Magellanic Clouds. Bernie's career as an active astronomer and engineer ended in 1985 when he reached the then-mandatory retirement age of 65. Bernie maintained an active interest in astronomy and radio telescope developments. Over time, his interests shifted from the large-scale structure of the universe to the very small scale of the quantum world and an active interest in relativity theory.

Through the 1980s and early 1990s, MOST was used for targeted observations of extended radio galaxies, clusters of galaxies, the Magellanic Clouds and supernova remnants. Discovery of the prompt radio emission (see Fig. 3.27) from supernova 1987A (Turtle et al., 1987), and its subsequent long-term monitoring, remains a highlight, along with the rapid response detections of radio emission from transient Galactic X-ray sources.

In 1991, development of MOST continued, with equipment upgrades that eventually permitted, among other things, an 843 MHz survey of the southern sky from declination −30° to −90°. The Sydney University Molonglo Sky Survey

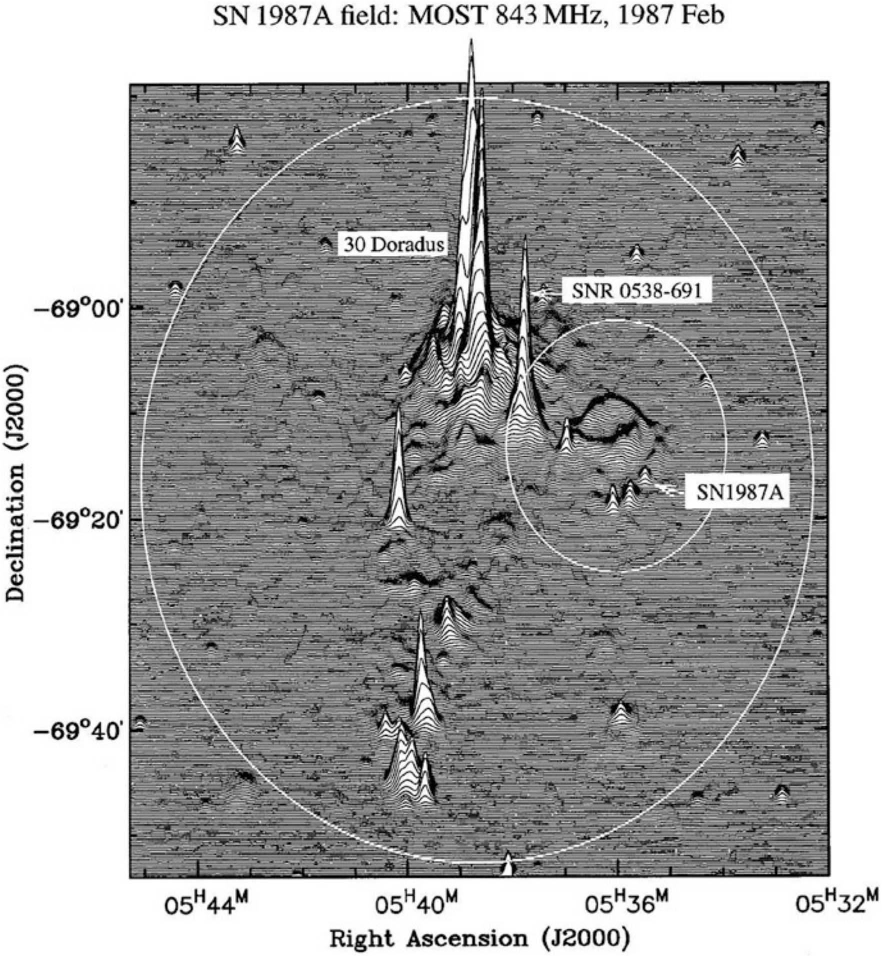

Fig. 3.27 The MOST discovery image of prompt radio emission from supernova 1987A at 843 MHz with a beamwidth of 45 arcsec and a 70 arcmin field of view. The peak flux density at around 1 GHz was about 150 mJy and occurred within 4 days of the supernova (after Turtle et al., 1987)

(SUMSS) began in 1997 and finished in August 2007 (Bock, Large, & Sadler, 1999; Mauch et al., 2003). A parallel project (a second epoch Molonglo Galactic Plane Survey, MGPS-2) mapped the southern sweep of the Galactic (Murphy et al., 2007). Both surveys are available online in catalogue format and as images.

In 2004, three-staged upgrades were proposed for the MOST as part of the Square Kilometre Array Molonglo Pathfinder (SKAMP) project to give the instrument its third major lease of scientific life. Unfortunately, the sourcing and programming of a correlator for the project proved difficult, and it was eventually shelved. Bailes et al. (2017) have written:

> In late 2013 a new system design (the UTMOST) was proposed that could add much more flexibility to the signal processing chain by using software and commodity off-the-shelf (COTS) servers and graphics processing units (GPUs) instead of Field Programmable Gate Arrays (FPGAs). The UTMOST design enabled time domain analysis modes and was motivated by the discovery of a new class of objects, the Fast Radio Bursts (outbursts from extragalactic objects that last roughly 5 milli-seconds, see, Lorimer, Bailes, McLaughlin, Narkevic, & Crawford, 2007)

By mid-2017, the UTMOST system is up and running. Roughly 100 pulsars are observed for precise timing each day, and up to this time three Fast Radio Bursts have been discovered. More than a half a century after Bernie Mills's inspiration was inaugurated at Molonglo, the instrument has a renewed life well beyond Bernie's original estimates of 15–20 years.

The Person

Bernie and Lerida had three children, Eric, Miranda and Deborah (later Shamynka). Lerida died in 1969.

Bernie was an intensely private and self-contained person, captured well in this comment from his second wife Crys née Lewis, whom he married in 1970:

> Bernie had two great passions in life. His research, his ever-questioning, ever-challenging mind was always open to new ideas. He also cared deeply for his students (though no doubt he didn't show it!), and he was thrilled when they succeeded. In our frivolous family conversations, he was usually silent, gently smiling. Then he would make one short, sharp, ironic comment which made us all laugh. He had a warm, amused smile and his laughter, when it came, was deep and soft. He was a modest, gentle, kind and unassuming man. Even as pain wracked him before death, he was saying over and over to us: "I'm sorry to be causing you all this trouble." And to me: "I'm sorry to be leaving you like this. I won't be able to look after you". (Mills, 2011)

For those who worked with him, Bernie was a great leader and for those who related to his striving for physical understanding, a great mentor. His legacy lives on throughout the world in the lives of the many students and colleagues whose research he encouraged and guided. His absolute integrity as a scientist and friend remains an example that all of us can strive to emulate.

Conclusion

The most significant contribution Mills made to radio astronomy was the revolutionary innovation of multiplying fan beams of a cross array to produce a high-resolution pencil-beam instrument. This new type of radio telescope is now named after him, the Mills Cross. He used this telescope design to explore the discrete radio sources, helping to elucidate their true nature and contributing, through surveys, a wealth of data that helped establish radio astronomy in the field of cosmology. The 1-mile cross telescope he built at Molonglo while at the University of Sydney is still in operation today and, through suitable modifications, is being used to explore the phenomenon of Fast Radio Bursts.

Professor Harry Messel, who recruited Bernie to the School of Physics, said at Bernie's memorial service: "Bernie was the mentor of many well-known researchers, several of whom are with us today, a quiet but wonderful leader". Many distinguished astronomers benefited from Bernie's astute mind and towering intellect. However, the legacy of Bernie Mills also lives on in his innovative telescope design that enabled important astronomical discoveries for a period far longer than the most optimistic expectations. These achievements are a tribute to his insight and vision. He will long be remembered for his immense contribution to low-frequency radio astronomy in Australia, and for the innovative design of his cross-type array which has found a wide application within and beyond the realm of radio astronomy.

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Chapter 4

Chris Christiansen: Telescope Design and Earth-Rotational Synthesis

Radio astronomy was not born with a silver spoon in its mouth. Its parents were workers. One parent was the radio-telephone; the other was radar (Christiansen, 1952).

Wilbur Norman "Chris" Christiansen (see Fig. 4.1) was born on 9 August 1913[1] in the Melbourne suburb of Elsternwick, where his father was the minister of the local Congregational church.

When Chris was a small child, his father was posted to Perth, and Chris started school at the local State primary school there. His father died of peritonitis at the age of 37 in the early 1920s. After his father's death, the family returned to Melbourne, where Chris's mother (Ilam Clarice Jones) taught music to support the family, and Chris went to the local primary school. Chris spoke of his mother and the environment he grew up in:

> Strangely enough, having spent all her time looking after her brats and teaching music, she seemed to have nothing to do in the evening but to play the piano, and being the last to go to sleep (because I was the eldest), I always went to sleep listening to Beethoven, Brahms and so on. (Crompton, 1997)

Chris subsequently went to Caulfield Grammar School where the headmaster had offered the family free tuition.

Chris was a keen hobbyist and an inventor from an early age. He became secretary of both the school's camera club and the radio club. He proudly described an early invention, as a schoolboy, that allowed one to write five lines at a time when given 100 lines as a punishment.

He became knowledgeable about crystal sets. The crystal receiver consisted only of a capacitor, an inductance, a galena crystal rectifier, a pair of headphones and a cat's whisker to make the connection. Chris experimented with home-made lead

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[1] On the occasion of what would have been Christiansen's 100th birthday, his achievements were celebrated with a Google Doodle on 9 August 2013. Unfortunately Google would not grant us permission to reproduce the doodle, however it is available online at: http://www.google.com/doodles/wilbur-norman-christiansens-100th-birthday.

R.H. Frater et al., *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, Astronomers' Universe, DOI 10.1007/978-3-319-65599-4_4

Fig. 4.1 Wilbur “Chris” Norman Christiansen (Courtesy of University of Sydney Archives P118)

sulphide because a piece of galena was too expensive. He talked, as well, of trying to make an amplifier with multiple cat’s whiskers in the pre-transistor era.

The University of Melbourne: Science, Philosophy and Politics

Chris started at the University of Melbourne in 1930, intending to study architecture but at the last minute choosing physics. He also observed social conditions around him. He described his reactions to the distress he saw during the Great Depression:

> As I walked to the University each morning through a rather poor district I saw people and their furniture being ejected from their houses. My early Christian beliefs that had not been buried by my now complete unbelief in the supernatural made me react very strongly. I joined the University Labor Club, which was very much to the left of the Labor Party and became very active in this. We published a journal called *Proletariat* and also a weekly news sheet and joined marches of the unemployed and were ridden down by the mounted police. At the University, there were some supporters of Mussolini and Hitler, and these tried to break up our meetings until the V.C. [Vice-Chancellor] stopped them. In addition to

> the Labor Club activities, I went to any other lunchtime meeting or musical recital that was taking place, and after lectures I joined the swimming club. I played hockey on one of the University teams and when the "lefties" were being attacked by the "fascisti", I joined the boxing club. (Frater, 1982)

Chris met Elspeth Hill at a weekend camp of the Melbourne University Labor Club in the early 1930s. When he later moved to take a job in Sydney, she moved with him to teach at Ravenswood School, and they married.

Chris graduated BSc in 1934 and MSc with First Class Honours in 1935 from the University of Melbourne. In 1931, he was awarded the Dwight Prize in Physics, which he said paid for his books, and the Kernot Prize in 1934.

While a postgraduate student at Melbourne in 1935, he discovered, with Crabtree and Laby, that "light" and "heavy" water could be separated by fractional distillation, indicating that special measures must be taken in purifying water prior to analysing its isotopic content. Laby was interested in building up a supply of deuterium for his planned programme of nuclear research.

Chris described aspects of this work and a dispute with Professor Laby:

> Heavy water (D_20) had recently been discovered, and it was already known that deuterium could be separated from hydrogen by fractional electrolysis. For that reason, old alkaline batteries that had been charged for many years had an electrolyte rich in deuterium. Such was available in cable-tram batteries in Melbourne, and I was given the job of collecting supplies of this electrolyte and, by further electrolysis, producing water with a very high component of heavy water. A second part of the work was to produce water almost free of deuterium and, by a very sensitive density measurement, to find the proportion of deuterium in natural water. This work was highly dangerous. All the gases from the electrolysis of water were collected together and forced through a nozzle and the jet set alight. If the nozzle velocity fell below the burning velocity, the flame could go backwards into the electrolysis chamber and a huge explosion might occur.
>
> Professor Laby had designed a device which allegedly reduced the size of the nozzle if the pressure fell and kept the jet velocity high enough for safety and avoided having to replace one blown-up research student by another one. I was suspicious of this and worked out the theory and found it would not work. I gave my calculations to the professor who angrily tossed them away and suggested that I might take up some other branch of scientific activity. I meekly said that I would try his device. I would attach it to an inflated balloon filled with the oxy-hydrogen mixture and light the jet. As the gas escaped and was burned, the pressure would fall, and we would see how the safety device worked. I set this up in the basement of the Physics school, lit the jet and ran upstairs. In a few minutes there was an enormous bang that caused great excitement throughout the building.
>
> I was then allowed to use my own safety device, which was simply a jar of sand between the jet and the source of gas. I got a prize for my MSc work rather than either death or the sack. The success of my thesis was not due to my heavy water production about which Laby told Tom Cherry (the professor of mathematics) "young Christiansen is going to blow himself up", but was the result of my finding that minute changes in the proportions of hydrogen and deuterium in common water could be produced by fractional distillation. Laby, as an authority on physical standards, was delighted that water density could no longer be used as a standard. "Well done, young Christiansen!". (Frater, 1982)

Chris's research career was on its way. In 1953, by which time he was working with CSIRO, he submitted his collected papers of the time and was awarded a Doctor of Science degree by the University of Melbourne.

Early Working Life

In 1937, after completing a 2-year appointment as Assistant Physicist with the Commonwealth X-ray and Radium Laboratory, Chris got a job at Amalgamated Wireless (Australasia) Ltd (AWA) in Sydney. AWA manufactured radios and communications equipment and operated the "Beam Wireless" system for Australia's overseas telecommunications.

Chris joined Geoffrey Builder and A.L. Green, pioneers in ionospheric physics research, at AWA's research laboratory in Sydney, where he concentrated on improving the "Beam Wireless" system and particularly on designing stacked rhombic antennas for overseas shortwave communications. He made an important contribution to securing Australia's international wartime radio communication linkages, and his experience in this area was also valuable in his later roles at CSIR.

Published in the *AWA Technical Review*, this work appeared subsequently in the International Radio Consultative Committee (CCIR) *High Frequency Directional Antennae* handbook and was widely referenced. Chris often joked that, "I got five bob[2] for my invention". The Overseas Telecommunications Commission, AWA's postwar successor in operating the shortwave services, made extensive use of the designs.

This period of Chris's career introduced him to a wide range of technologies and to some of the best technical people of the time, including Geoffrey Builder, A.L. Green, Ernie Benson and Ruby Payne-Scott and Lindsay McCready. He encountered many "hands-on" learning opportunities that he would carry with him into his later life.

The Radiophysics Division of CSIR/CSIRO

Chris had a long-standing interest in astronomy and, in 1948, wrote to the Radiophysics Division of the Council of Scientific and Industrial Research (CSIR, after 1949 CSIRO), enquiring about positions. The Division was then headed by E. G. "Taffy" Bowen and the radio astronomy group by J. L. Pawsey. Chris was offered a position in Pawsey's group (see Fig. 4.2).

Chris enjoyed the benefits of joining an environment that had been fostered by CSIR's long-standing Chief Executive Officer David Rivett: "get the best people

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[2] A "bob" is slang for a shilling or five pence.

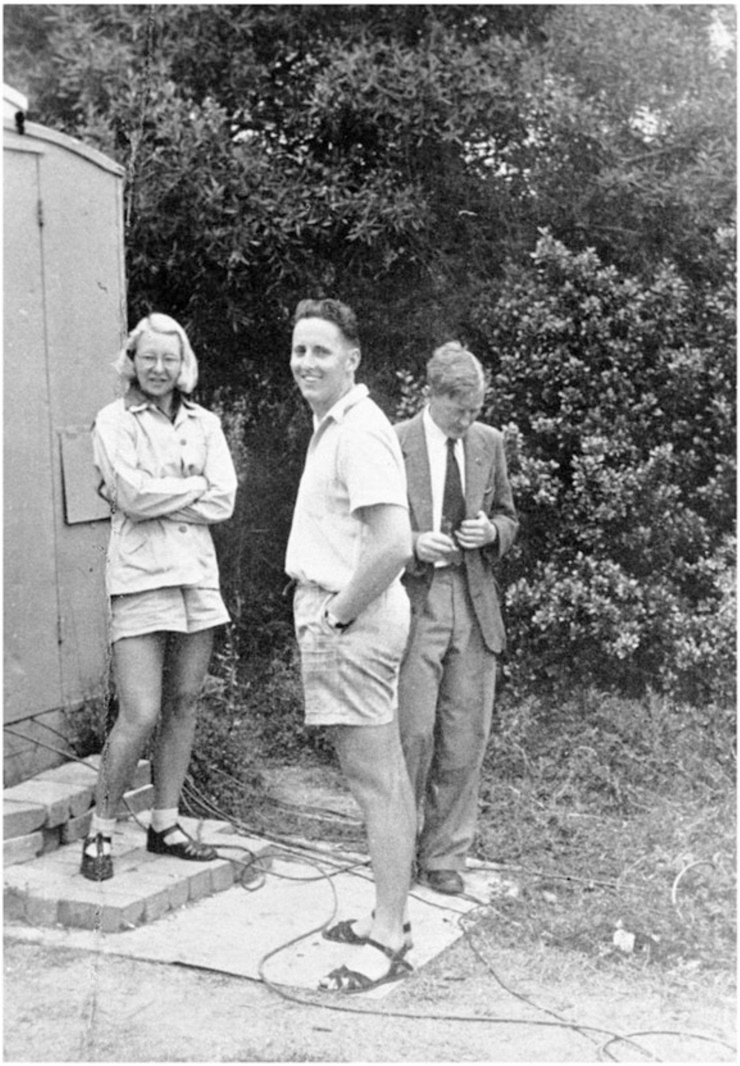

Fig. 4.2 Christiansen (*right*) at Potts Hill in 1948 with Ruby Payne-Scott and Alec Little, soon after joining the Radiophysics group (CSIRO Radio Astronomy Historical Photographic Archives B14315)

possible, give them the needed resources and let them run free". Realistically, the resources were never plentiful, but the freedom and encouragement were there. In this regard, Joe Pawsey was a man in the Rivett mould, and he earned enormous respect from all those who worked with him. Chris was a great admirer and in his own later roles emulated Pawsey's approach.

Chris was appointed to a senior role within Radiophysics. He became the leader of the solar research programme at the newly established field station at Potts Hill in the western suburbs of Sydney. The main radio telescope there was a 16 × 18-ft wartime experimental radar (see Fig. 4.3) that had been relocated from the Georges Heights field station to Potts Hill in time for the 1948 solar eclipse (see Wendt, Orchiston, & Slee, 2008). Chris organised observations of partial solar eclipses with D. E. Yabsley and B. Y. Mills at a wavelength of 50 cm in 1948 and with Yabsley at

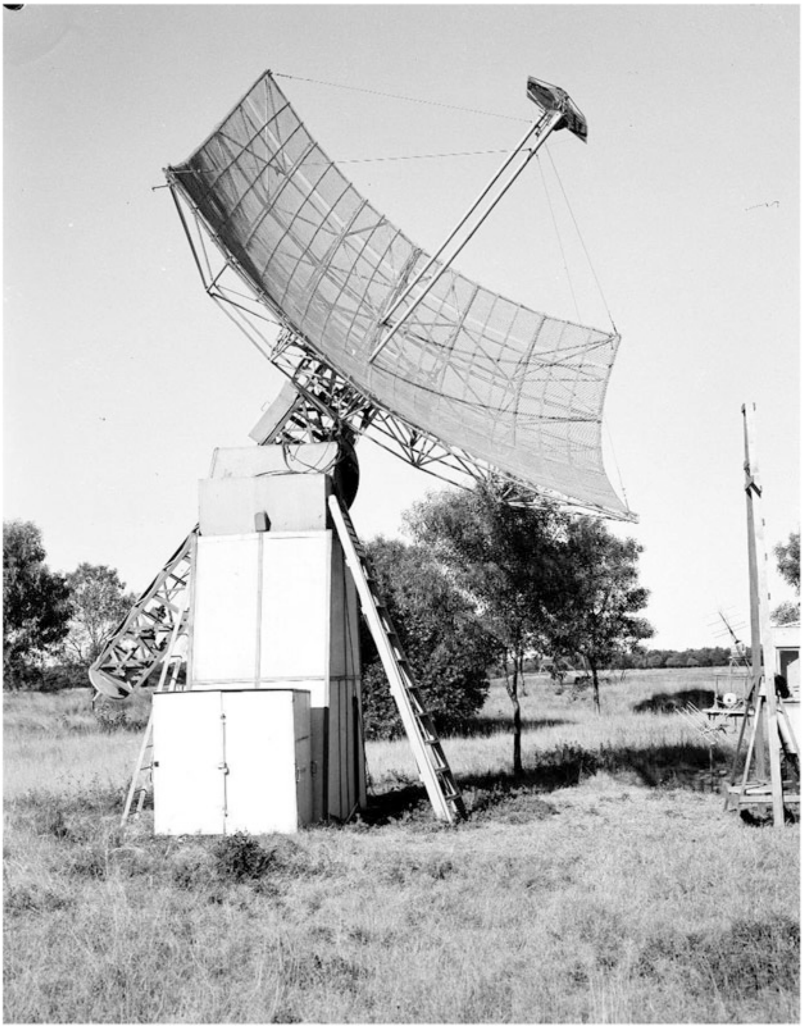

Fig. 4.3 The 16-ft × 18-ft aerial at Potts Hill field station in May 1949. This aerial had been relocated from Georges Heights and was used by Christiansen to observe the partial solar eclipse of November 1948 and resulted in his first publication on radio astronomy (CSIRO Radio Astronomy Historical Photographic Archives B1903-1)

a wavelength of 25 cm in 1949. These observations showed that regions of the sun of high radio emission (associated with sunspots) had dimensions of about one-tenth of the solar diameter (see Fig. 4.4). They were the subject of Chris's first astronomy publication (Christiansen, Yabsley, & Mills, 1949a, b).

This discovery and Chris's frustration at the inefficiency of depending on eclipses for measurements led to the development of the "grating array" that achieved high resolution as a result of its length and produced multiple responses on the sky[3] separated by a number of solar diameters (see Fig. 4.5). The first grating telescope (see Figs. 4.6 and 4.7) at Potts Hill in 1951, allowed the distribution of radio brightness across the sun to be studied as the sun drifted through the responses during the day (see Fig. 4.8). This telescope array was a very manual affair, requiring the observers to run up and down the array adjusting the pointing of the individual antennas to follow the sun. Chris and his colleagues found that the enhanced continuum emission at 21 cm came from regions in the lower corona of the sun. The dimensions of these regions and their height above the photosphere (visual surface of the sun) could be determined for the first time.

A second investigation concerned the background or "quiet sun" radiation at 21 cm. David Martyn had predicted limb brightening[4] (Martyn, 1946), but the Cambridge radio astronomy group had conducted observations that discounted the possibility. Chris, with J. A. Warburton, observed limb brightening with early experiments using an east-west array. They later made use of two gratings, one in an east-west and one in a north-south direction (see Fig. 4.9), to observe the sun from dawn until dusk to obtain the two-dimensional intensity distribution. This clever observation showed marked limb brightening in the equatorial zones but none at the poles. By producing "strip scans" and performing many laborious hand calculations over months of effort, they produced an image, shown in Fig. 4.10.

This approach was the first known application of earth-rotational synthesis and produced, for the first time, a radio map with a resolution as fine as 4 min of arc.

One of the people who worked with Chris at this time was Govind Swarup, who had come to Australia under the Colombo Plan from the National Physical Laboratory in India. He did the calculations required (Fourier transforms[5]) to produce the images by hand. As he said in his paper, "Reminiscences regarding Professor W. N. Christiansen": "I learned the powerful technique of radio interferometry from Chris in 1953 and I haven't looked back".

When the grating array at Potts Hill was no longer being used, Pawsey and Chris arranged for it to be transferred to India where it ultimately became the Kalyan Radio Telescope and began observing in 1965 (Goss, 2017) (see Fig. 4.11).

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[3] See Appendix A.

[4] The absence of circular symmetry with enhanced brightness at the equatorial regions of the sun. The cause is the high temperature of the corona relative to the inner atmosphere of the sun.

[5] The mathematical operation applied to the observational data in order to produce an image of the radio sky.

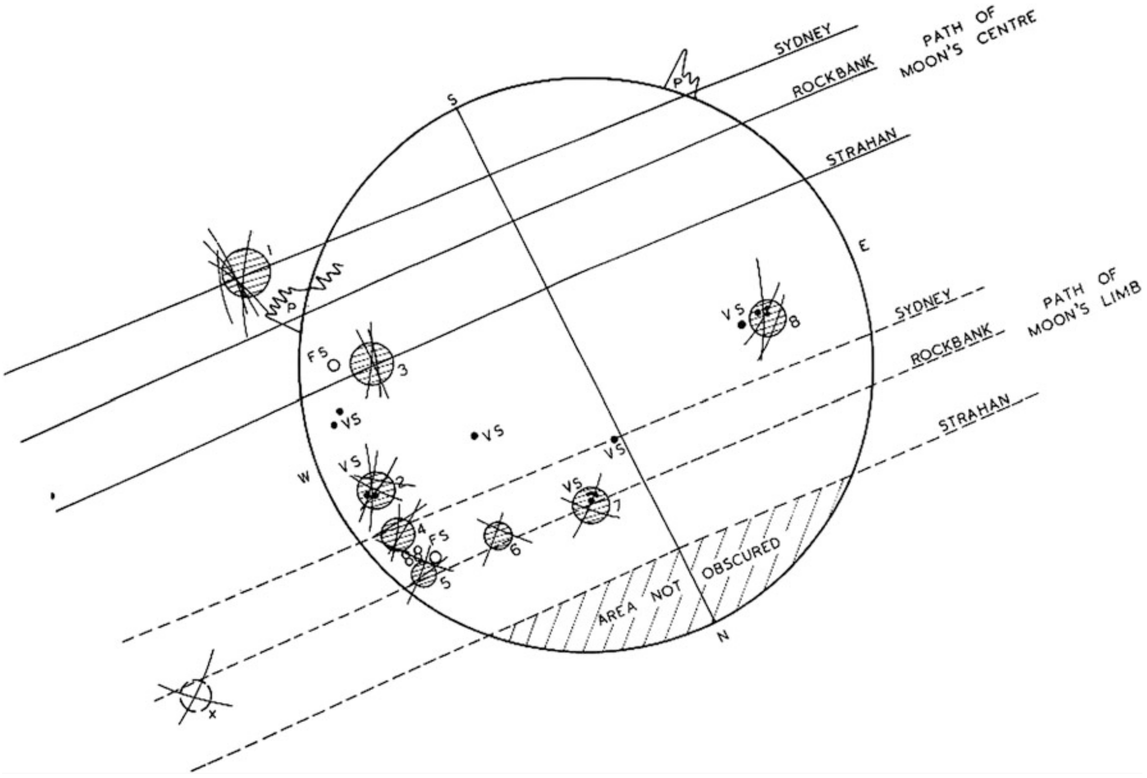

Fig. 4.4 A diagram of the sun from the November 1948 partial solar eclipse showing the triangulation of radio sources seen from Potts Hill near Sydney, Rock Bank in Victoria and Strahan in Tasmania. *VS* visible sunspot group; *P* prominence; *FS* position of sunspots 27 days before the eclipse. Note the position of the radio source on the *upper left* high in the solar corona above the visible solar prominence. Not all radio sources were closely correlated to visual sunspots (CSIRO Radio Astronomy Historical Photographic Archives B1983-3)

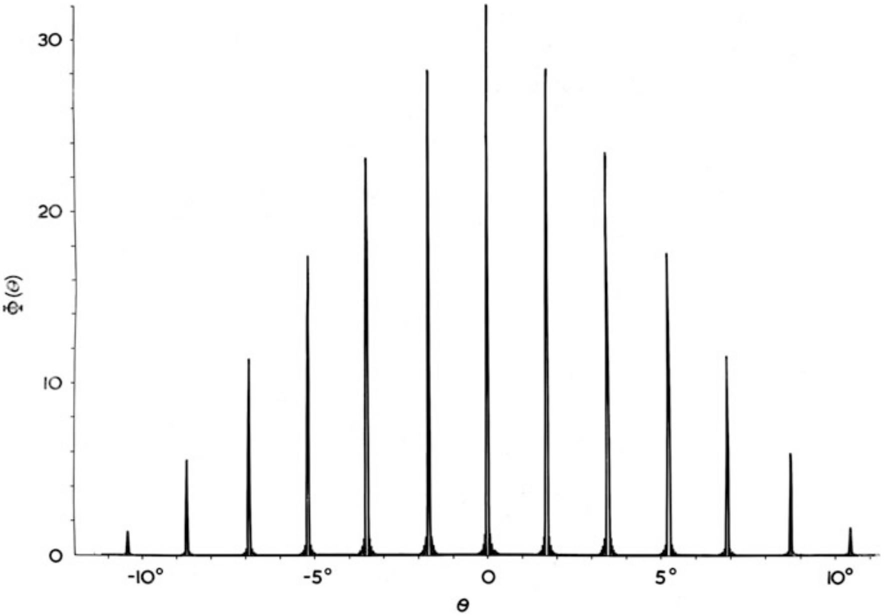

Fig. 4.5 Beam response diagram for the 32-element array. The power received from the source is shown on the *Y*-axis and the direction of the source relative to the array beam on the *X*-axis (after Christiansen & Warburton, 1953: 192)

The Hydrogen Line

In 1951, news came from E. M. Purcell in America that one of his students, H. I. Ewen, had found a particular radio spectral line from space that would make it possible to look, not at the hot or active parts of the interstellar medium, but at the hydrogen in the cold regions (Ewen & Purcell, 1951). In contrast to optical wavelengths, there was no absorption due to the pervasive galactic dust.[6] This important discovery had been predicted by Hendrik van de Hulst in Holland. Purcell sent requests to Joe Pawsey and the Dutch groups to help confirm the discovery.

Chris worked with J. V. Hindman on this project:

> All we knew was that this had been seen with a fixed aerial when the Milky Way went through. With Jim Hindman as my assistant I got stuck into this very rapidly, using all sorts of old junk that we could collect. We did have to make up one special bit of instrumentation. Within 6 weeks we confirmed that the radiation was coming from the Milky Way, but we went further and mapped it all over the Milky Way, showing that, in fact, it had exactly the same shape as the Milky Way. Moreover, because we were doing it in a special way, we

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[6] Optical radiation in the Milky Way is absorbed by dust particles in the interstellar medium. The dark bands in the Milky Way arise from this dust (size about one micron). At radio frequencies the dust is completely transparent.

Fig. 4.6 A prototype dish for the solar grating array undergoing testing at Potts Hill in October 1950. (CSIRO Radio Astronomy Historical Photographic Archives 2294-1)

> were able to show there were spiral arms in our Galaxy—the first radio evidence that we were living in a spiral galaxy. (Frater, 1982)

As Chris remarked later:

> Our research was done crudely, but it was good fun, and the results were exciting. When Purcell's research student Ewen came over (to Sydney for the 1952 URSI meeting) and saw the gear I had, with cables lying all over the floor and ancient oscillators, he said,

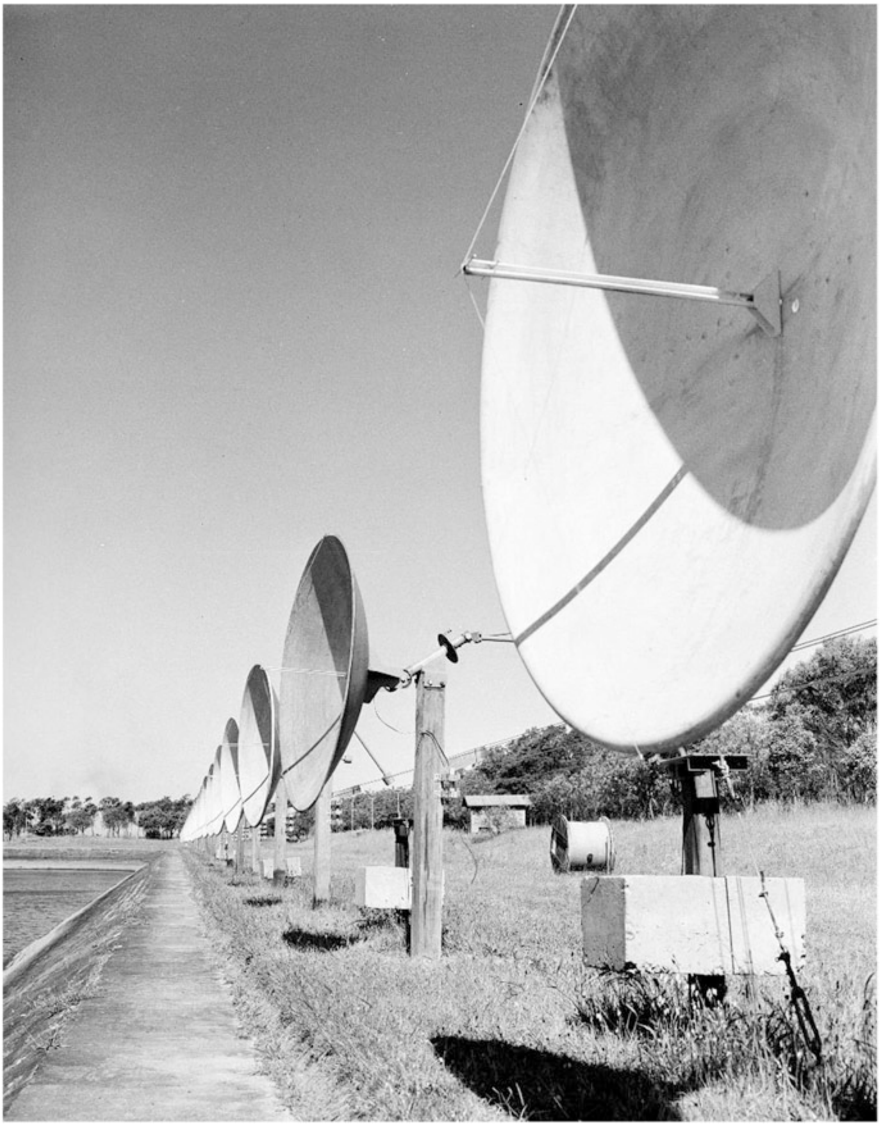


Fig. 4.7 The completed 32-element solar grating array on the southern bank of the Potts Hill No. 1 reservoir in November 1951. The array is oriented on an east-west baseline. Each dish is 6 f. in diameter with the combined output of the array producing a beam with a resolution of 3 arcmin at 1420 MHz (CSIRO Radio Astronomy Historical Photographic Archives B2638-3)

> "My God, I can understand why you could do it in 6 weeks and it took me 2 years!". (Frater, 1982)

Chris and Jim Hindman continued with their crude equipment. They had not only confirmed the discovery of 21 cm radiation from ground-state hydrogen in the

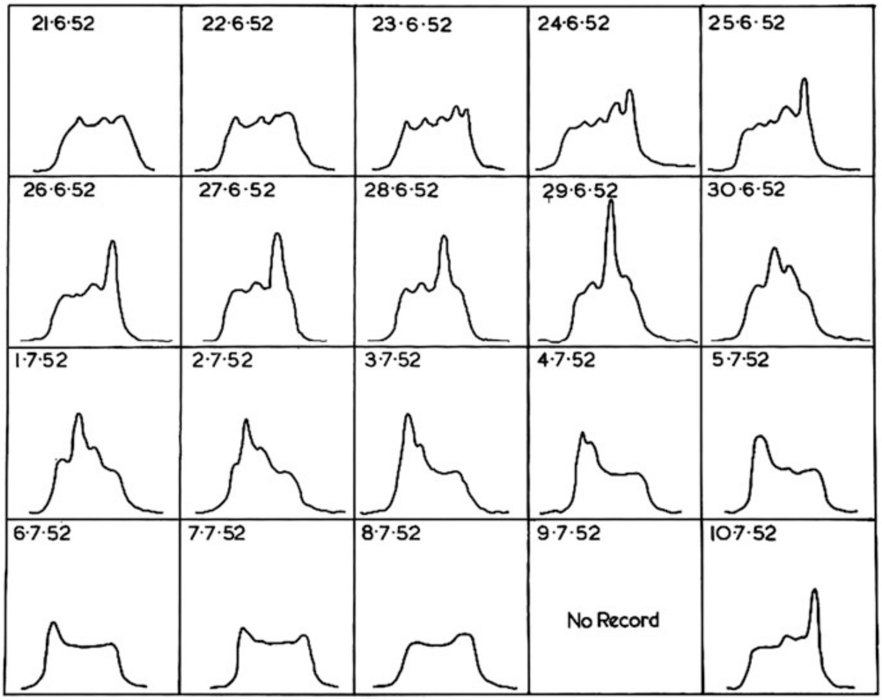


Fig. 4.8 Examples of the one-dimensional scans of the solar disk at 1420 MHz produced using the solar grating array on successive days. Each scan shows the solar radio emission across the sun's disk. The peaks in emissions on different days relate to the presence of radio plages in the solar corona. The enhanced emission appears to move across the solar disk from right to left from 24 June to 6 July as the sun rotates (CSIRO Radio Astronomy Historical Photographic Archives B2849-1)

Milky Way but had made the first survey of H-line emission from space, obtaining the first radio evidence of the existence of spiral arms in our galaxy, the Milky Way (see Fig. 4.12).

A French Interlude, then Fleurs and the "Chris Cross"

The French were very interested in the work at Radiophysics, and, at the URSI General Assembly in Sydney in 1952 (see Fig. 4.13), Chris was invited to go and work in France. He spent 1954 at the Meudon Observatory, where he learned "a lot about France and optical astronomy". When he returned to the Radiophysics Laboratory, he started on a new project (see Fig. 4.14), which ultimately became known as the "Chris Cross".

Fig. 4.9 The 16-element north-south arm of the solar grating array in July 1953 at Potts Hill. The array was located on the eastern bank of the No. 1 reservoir at Potts Hill. The view in the photograph is from the northern end of the array looking south. The E-W arm can be seen in the background on the southern bank of the reservoir. By combining data from the 32-element E-W arm of the array and the N-S arm, it was possible to construct a two-dimensional image of the solar radio emission at 1420 MHz (CSIRO Radio Astronomy Historical Photographic Archives 3116-1)

This new telescope, which combined the grating approach from Potts Hill with the Mills Cross principle conceived by Bernie Mills, was subsequently built at the Fleurs field station (see Figs. 4.15, 4.16, 4.17 and 4.18). It provided daily two-dimensional images of the sun with a resolution of 3 arcmin from 1957 onwards. These images were built up by scanning with a pencil beam to produce a "raster scan" where the beam moved up one step at a time as the sun went through successive grating lobes with the rotation of the earth (see Fig. 4.19). The radio telescope at Fleurs (see Fig. 4.20) was the first of a number of similar instruments built around the world.

During this period at CSIRO (1948–1959), Chris was awarded the Syme Prize for Research by the University of Melbourne in 1959, and a paper describing the design of the grating cross received the Fleming Premium of the Institution of Electrical Engineers in 1961.

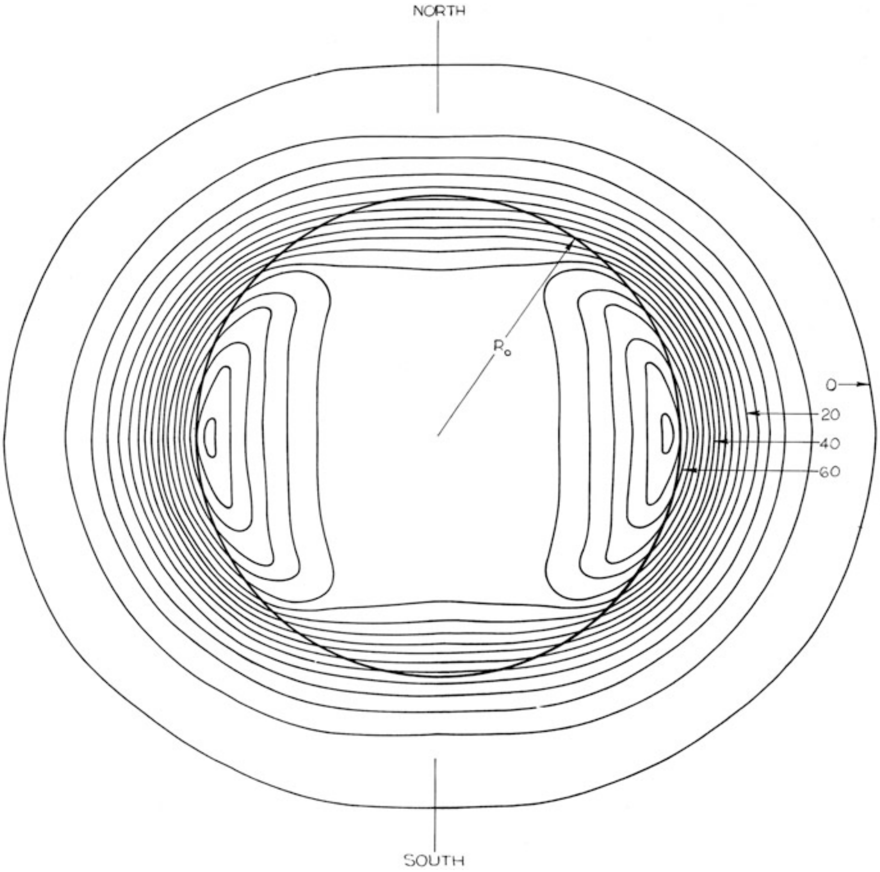


Fig. 4.10 A two-dimensional derived radio brightness distribution of the “quiet” sun at 1420 MHz calculated from observations from the N-S and E-W arms of the solar grating array as the sun moved across the sky (see Christiansen & Warburton, 1955: 482). To produce this image took months of laborious Fourier transform calculations and was the first application of earth-rotational synthesis which today underpins the imaging techniques of radio astronomy. The image showed the sun’s radio emission was not circularly symmetric and showed strong limb-brightening, something that had been missed by earlier Cambridge observations (CSIRO Radio Astronomy Historical Photographic Archives B3759-2)

A Parting of Ways, Electrical Engineering at the University of Sydney and Return to Fleurs

With the planning and building of the Giant Radio Telescope (GRT) at Parkes, funding for arrays of small instruments waned, so Chris left CSIRO. He was appointed to the Chair of Electrical Engineering at the University of Sydney in 1960. He did not take up his post immediately but first spent 15 months at Leiden

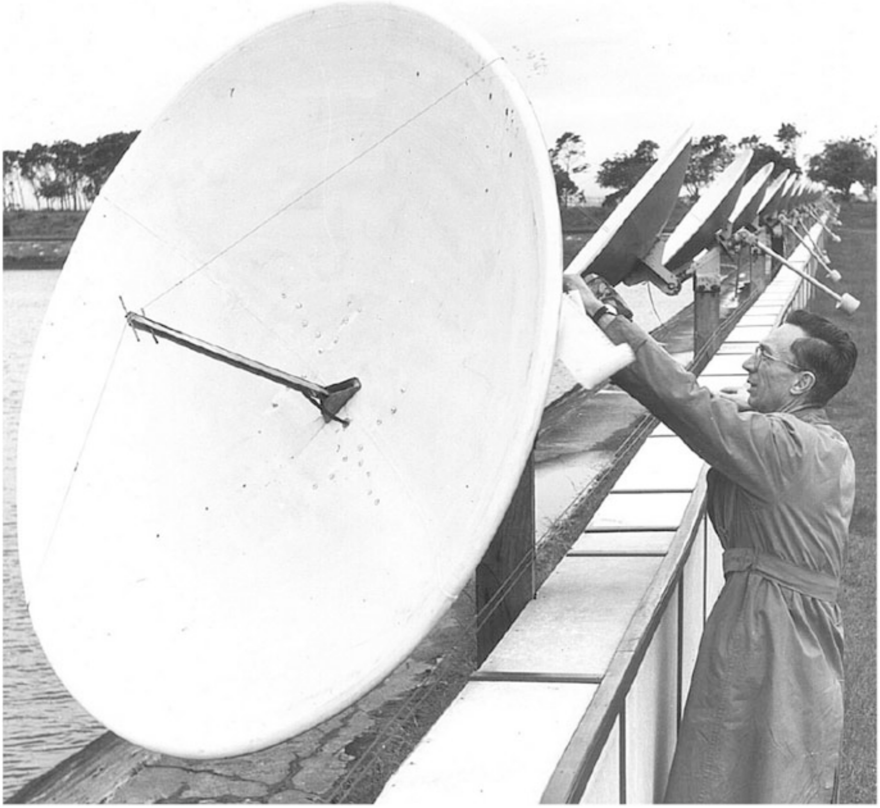


Fig. 4.11 Pawsey with Christiansen's solar grating array at Potts Hill in 1952 (Courtesy of the CSIRO Radio Astronomy Image Archive 2842-63)

University, at the invitation of Professor Jan Oort, the leader of an international design team for the 400 MHz Benelux Cross Project. Here, he worked with the Swedish astronomer Jan Högbom, who had finished a PhD with Martin Ryle at Cambridge in August 1959 on "The Structure and Magnetic Field of the Sun". His thesis included chapters on aperture synthesis theory and earth-rotational synthesis. The Belgians pulled out of the project, and the Benelux Cross was abandoned, but Chris maintained an active collaboration with the Dutch group as they developed what ultimately became the Westerbork Synthesis Telescope. He and Jan Högbom wrote a book together called *Radiotelescopes*. It was published by Cambridge University Press in 1969, with a second edition in 1985. A Russian translation by Yuri Ilyasov appeared in 1971 as well as a Chinese translation by Chen Jian-sheng in 1977.

In Sydney, Chris attempted, unsuccessfully, to gain financial support to build a "hole-in-the-ground" spherical reflecting telescope 30 m in diameter for use at

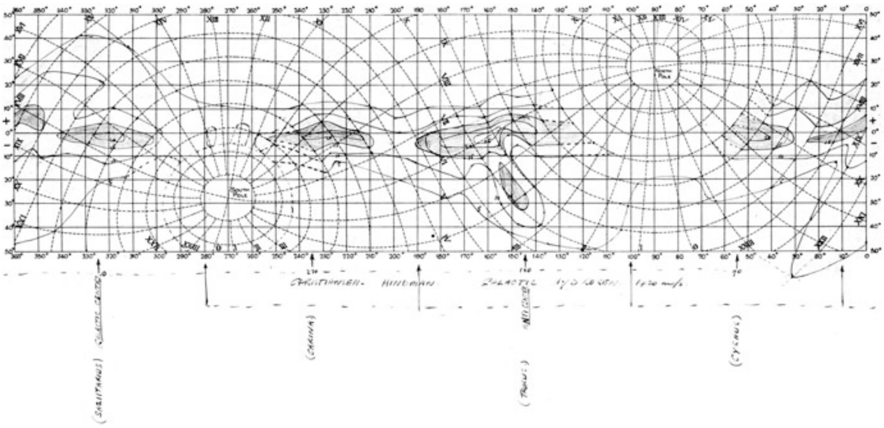


Fig. 4.12 An early survey map of the distribution of neutral hydrogen (HI) gas along the galactic plane produced by Christiansen and Jim Hindman using the 16-ft × 18-ft aerial at Potts Hill together with the makeshift 21 cm receiver they constructed following news of the discovery of the HI emission line in the USA in 1951. Their survey produced the first radio evidence for the structure of spiral arms in our galaxy (CSIRO Radio Astronomy Historical Photographic Archives B2632)

Fig. 4.13 Chris is demonstrating part of the telescope at Pott's Hill to Professor B. van der Pol (second from the *right*), the famous Dutch engineer and scientist. There also, with his black hat on, is Sir Edward Appleton who won a Nobel Prize for his work on the Ionosphere. Fred White is standing in the centre. This image was taken during the URSI General Assembly in Sydney in 1952 (Courtesy of the CSIRO Radio Astronomy Image Archives B2842)

Fig. 4.14 The aerial on the *left* is a prototype of aerial for the planned "Chris Cross" array to be constructed alongside the Mills Cross at Fleurs field station. Here, it is being tested alongside the N-S arm of the solar grating array at Potts Hill in December 1955 (CSIRO Radio Astronomy Historical Photographic Archives B3881-2)

millimetre wavelengths. He was keen to have a big project that could be used to stretch the minds of postgraduate students. Undeterred by the failure of the "hole-in-the-ground" proposal, he continued looking for ways forward. After hearing from Paul Wild that the field station at Fleurs was to be demolished, he approached CSIRO and requested that CSIRO donate the grating cross array at Fleurs to the University of Sydney.

Joe Pawsey, Chris's old boss at Radiophysics, was anxious to support him. In a paper titled "The Present Difficulties in Australian Radio Astronomy", dated 31 March 1960, Pawsey set out his assessment of the state of radio astronomy in the era preceding the opening of the Parkes radio telescope on 31 October 1961. The paper was submitted to the CSIRO Executive in order to gain support for other new initiatives in Australia: "The report recommends that CSIRO should be prepared to co-operate very closely with the new Professor of Electrical Engineering at Sydney University". Pawsey pointed out that the curtailment of the solar work at Fleurs had led to a plan for the development of high-resolution techniques applicable to cosmic problems. The construction of a compound interferometer by adding an 18 m paraboloid to the existing solar array of 5.8 m antennas had been

Fig. 4.15 Construction of the Chris Cross underway at Fleurs field station October 1956. This small hut near the *centre* of the array was used to assemble the components of the cross. To the *left* of the hut is the aerial frame jig (CSIRO Radio Astronomy Historical Photographic Archives B5006-7)

discussed (see Fig. 4.21). Pawsey concluded by stating that Christiansen wanted to co-operate with the CSIRO Division of Radiophysics: “I believe this would be to our mutual advantage and consider our cooperation should take the form of a joint project”.

Christiansen said later: “CSIRO was very generous. We took over the whole field station”.

Chris saw the opportunity for a significant and challenging project and set about changing the arms of the Chris Cross instrument to convert it from one of low sensitivity and 3 arcmin resolving power, designed for solar observations, into a high-resolution rotational synthesis telescope at roughly the same wavelength of 21 cm as the previous Fleurs crossed multi-element interferometer. As the “Fleurs

Fig. 4.16 An aerial view of construction work on the Chris Cross in November 1956 showing the construction huts near the *centre* of the array, some completed aerials and the hooped steel for producing more aerials (CSIRO Radio Astronomy Historical Photographic Archives P10329-6)

Synthesis Telescope", it would be used for galactic and extragalactic astronomical observations.

The Fleurs Synthesis Telescope was built utilising the infrastructure of the Chris Cross. The compound interferometer at 1415 MHz, or 21 cm, was formed by adding two new 13.7 m antennas on the east-west and north-south arms with a total baseline of 800 m (see Fig. 4.22). Astronomical sources could be tracked for 8 h per day. With this combination, roughly circular beams could be achieved from the celestial equator to a declination of $-80°$. The resolution was 40 arcsec after two times 8 h, once with the east-west array and once with the north-south array. During its years of operation, the Fleurs Synthesis Telescope provided the highest-resolution radio telescope (apart from long-baseline interferometry) in the southern hemisphere.

Over a period approaching 25 years, the Fleurs Synthesis Telescope was an important test bed for PhDs in Electrical Engineering and a training ground for numerous scientists who have played major roles, not just in radio astronomy but in Australian industry, universities and the CSIRO. Chris had a strong belief in the benefit for students of working on large complex projects in a team environment, and their subsequent success is a significant tribute to him.

During the lifetime of the Fleurs Synthesis Telescope, a number of technical improvements were made that expanded the capabilities of the instrument. Its sensitivity was improved in late 1975 by about a factor of four with the addition

Fig. 4.17 The completed Chris Cross at Fleurs field station in November 1957. The view is from just north of the *centre* of the array looking south along the N-S arm. Each arm had 32 5.8 m open mesh dishes operating at 1420 MHz and producing a 3 arcmin pencil beam (CSIRO Radio Astronomy Historical Photographic Archives B5219-2)

of more sensitive receivers to the 13.7 m antennas. Starting in 1976, plans were being made to extend the Fleurs Synthesis Telescope to a longer baseline and hence greater angular resolution. By 1984, the resolution of the array was doubled to about 20 arcsec by the addition of two new 13.7 m antennas.

During this period, the Fleurs Synthesis Telescope produced numerous radio images and astrometry at the arcsec level; the success of these research endeavours was a major stimulus to the planning of the Australia Telescope (AT) that began in the early 1980s. The Fleurs Synthesis Telescope was a hands-on test bed for many of the concepts that were later used at the AT. An additional indirect influence was the pronounced impact of the Fleurs Synthesis Telescope on the Australian astronomical community; the breakthroughs brought about by high-sensitivity, high-resolution radio images showed the need for a high-resolution multi-frequency instrument, later to be the Australian Telescope Compact Array at Narrabri.

Chris created a unique environment at the Fleurs Synthesis Telescope, characterised by a symbiotic relationship between young innovative electrical engineers and radio astronomers (see Fig. 4.23); the two groups were learning from each other as technical innovations led to challenging radio astronomical

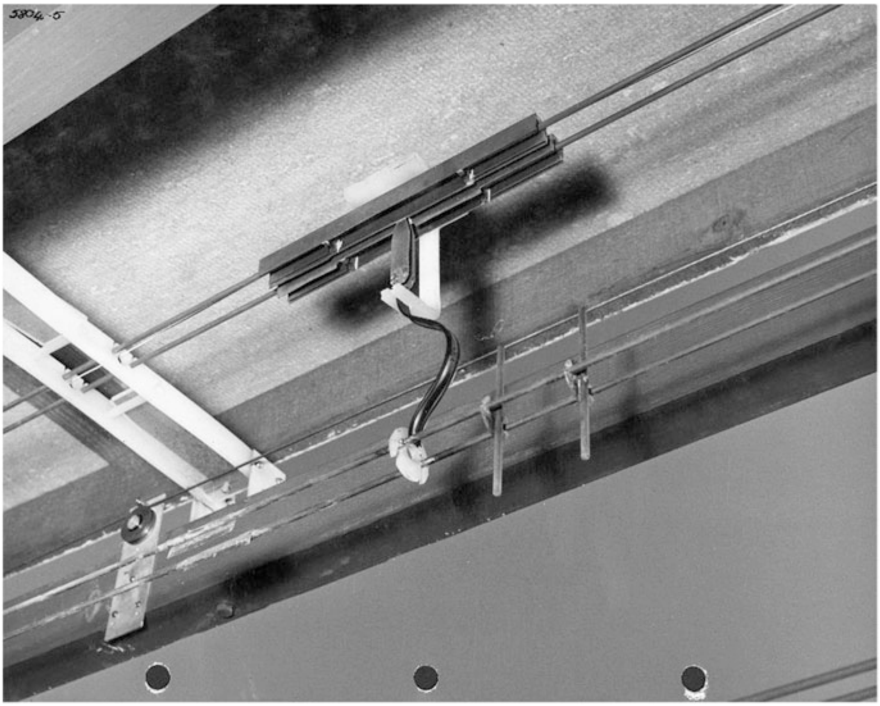
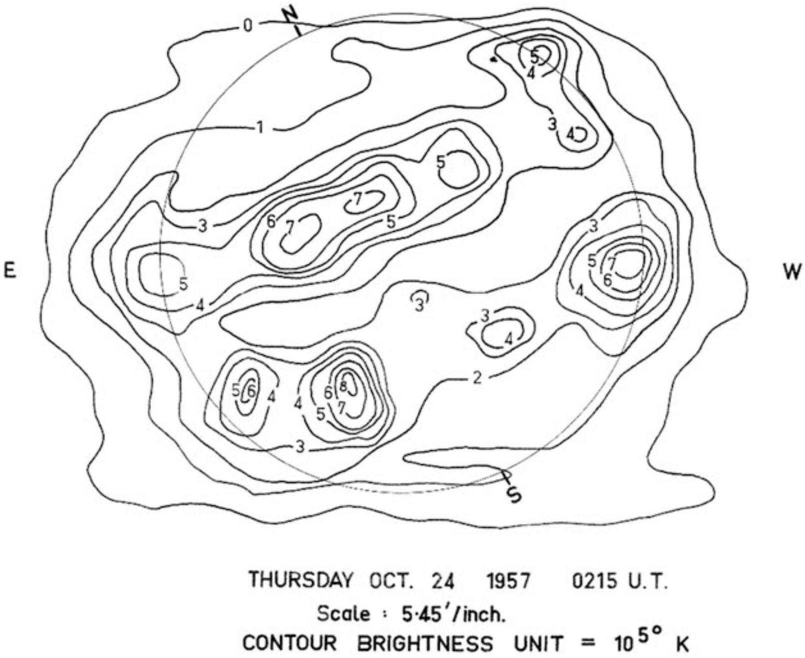


Fig. 4.18 A close-up of the open pair transmission lines used on the Chris Cross. Christiansen used this low-cost but effective transmission line design throughout his career. In fact, his first published paper was "An Exponential Transmission Line Employing Straight Conductors" appearing in The Proceedings of the I.R.E. in 1947 (CSIRO Radio Astronomy Historical Photographic Archives R5804-5)

observations. A prominent example was the solution of the projection of the three-dimensional space used by radio astronomers in aperture synthesis (Appendix A) into a simplified two-dimensional coordinate system (Frater & Docherty, 1980).

Starting in 1975, the Fleurs Synthesis Telescope was in full operation at 21 cm in the continuum, with a large number of observations completed with the east-west arm. In late 1975, the north-south arm came into operation. For most fields, the final observational product consisted of two 8 h observations with the east-west and north-south arms. Circular beams were possible over most of the southern sky. For the next 13 years, the Fleurs Synthesis Telescope was used extensively by more than 75 scientists to publish 69 papers. We provide here a short summary of a number of highlights of the early years of Fleurs Synthesis Telescope research (roughly up to the time of Chris Christiansen's retirement from the University of Sydney in 1979).

In an initial publication from 1976, Frater, Watkinson, Retallack and Goss described a calibrator grid of compact radio sources. This set of calibration positions for the southern sky was established by observations of four sources of



THURSDAY OCT. 24 1957 0215 U.T.
Scale : 5·45′/inch.
CONTOUR BRIGHTNESS UNIT = 10^{5}° K

Fig. 4.19 An example of a contour map of the 1420 MHz solar radio emission derived from observations using the Chris Cross showing the distinct radio plage emissions. These images were produced on a daily basis (CSIRO Radio Astronomy Historical Photographic Archives B5419)

previously known positions over the declination range −75° to −13°. These observations were necessary in order to carry out routine observations over most of the southern sky at declinations outside the ranges of the major high-resolution radio telescopes in the northern hemisphere.

A keynote publication of this era was a paper by Christiansen et al. (1977), “Observations of 15 Southern Sources with the Fleurs Synthesis Telescope”. This publication highlighted the capabilities of the Fleurs Synthesis Telescope. The paper included images of the famous radio galaxies Centaurus A, Pictor A, PKS 0349-27.9 and the low Galactic latitude source G309.7+1.7, a likely extragalactic source close to the Galactic plane. Christiansen was also a co-author in a publication by Goss et al. (1977b) “IC 4296: A Double-double radio galaxy”.

In 1976, the astronomical community was excited by the discovery of the second optical pulsar, following the discovery of the Crab pulsar 7 years earlier. The newly completed high-resolution Fleurs Synthesis Telescope played a key role in this discovery by the determination of the sky coordinates at 1415 MHz (observations 4–6 September 1976). The Molonglo Radio Telescope was also used in this determination. The accuracy of the combined position was about 1 arcsec (Goss, Manchester, McAdam, & Frater, 1977a). A few months later (24–27 January 1977), a group of astronomers (including Goss and Manchester) detected optical pulses

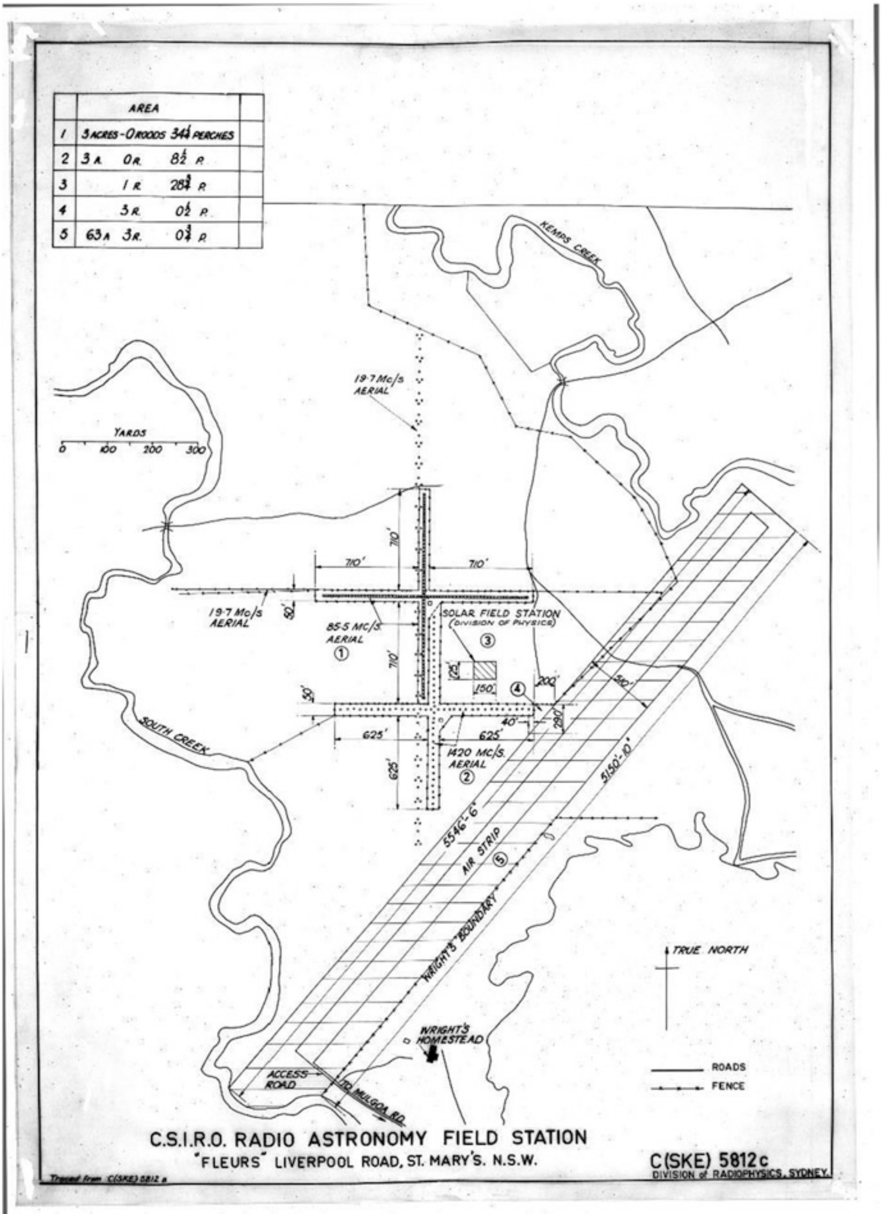


Fig. 4.20 A plan of the Fleurs field station showing the locations of the three cross arrays constructed at the site. The southern cross is the Chris Cross used for solar observations; the northern cross is the Mills Cross which shared a common centre with the low frequency Shain Cross (19.7 MHz) (CSIRO Radio Astronomy Historical Photographic Archives B5815)

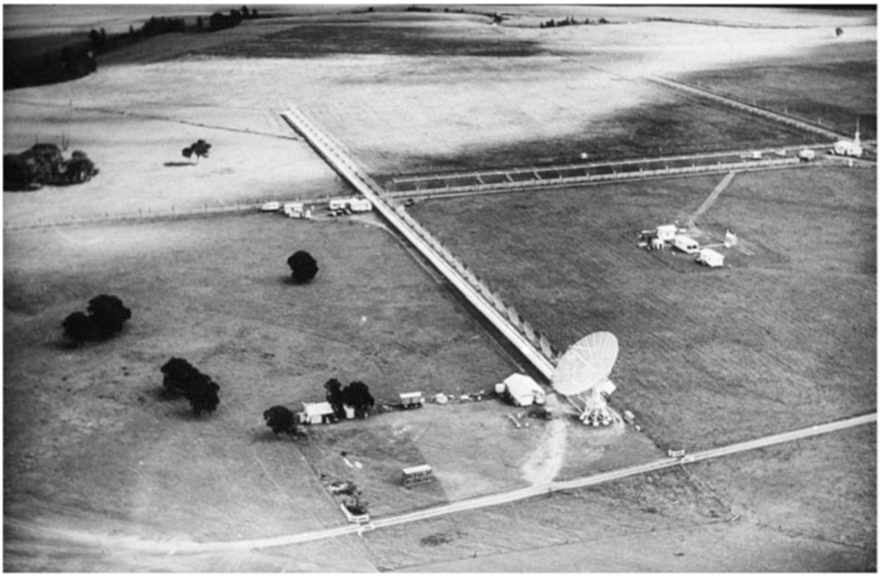


Fig. 4.21 An aerial view of Fleurs field station in June 1961 showing the 18 m dish "Kennedy" on the eastern end of the Chris Cross. The Kennedy dish was inaugurated on 16 May 1961 and later moved to Parkes. Together with the E-W arm of the Chris Cross, it was used as a compound interferometer operating at 1420 MHZ. The view is from the east looking west. The Mills Cross is on the right. The cluster of buildings between the Chris and Mills Cross is the Division of Physics solar station which included a coronagraph (CSIRO Radio Astronomy Historical Photographic Archives B6447)

from the 23.7 mag star M (of Lasker, 1976) using the Anglo-Australian Telescope based on the new radio position. The paper was published in *Nature* on 21 April 1977 by P.T. "Pat" Wallace and 11 co-authors.

The detection of the second optical pulsar had a major impact throughout the astronomical world. On 3 May 1977, John Bolton wrote to his former Chief of the Division of Radiophysics, Taffy Bowen, who was in the USA at this time (National Archives of Australia C 4661): "A combined effort from Greenwich, the AO [AAT] and RP [Radiophysics] recently found the optical pulsar from the Vela pulsar in the position resulting from a combined effort at Molonglo and Fleurs. It's [2 million] times weaker than the Crab (in the optical)".

In the late 1970s, an important new component of the Fleurs Synthesis Telescope research programme was initiated: the study of galactic supernovae remnants (SNR). In 1977, Lockhart, Goss, Caswell and McAdam published a paper providing the first high-resolution image of the unusual SNR G282.0+1.8 at 1415 GHz. This image led to an optical identification by Goss, Shaver, Zealey, Murdin and Clark (1979), showing this to be an oxygen-rich SNR. The modern history of the source is summarised by Gaensler and Wallace (2003), who used data from the Australia Telescope Compact Array. Remarkably, the ATCA images are quite similar to the

Fig. 4.22 An aerial view of the Fleurs Synthesis telescope in 1969. This used the original Chris Cross together with larger 13.7 m aerials to form a longer baseline and a much more sensitive synthesis instrument with a resolution of 45 and later 23 arcsec. The view is from the east looking west. The eastern 13.7 m aerial is visible on the immediate eastern end of the cross. The western 13.7 m aerial is visible just short of the creek line. The Mills Cross is visible to the right (CSIRO Radio Astronomy Historical Photographic Archives N9114-3)

Fleurs Synthesis Telescope 20 arcsec image made in the mid-1980s by Milne et al. (1985) using the expanded Fleurs Synthesis Telescope.

In the period 1979–1987, 12 additional publications appeared with descriptions of the 1415 MHz properties of numerous SNR in the galaxy as observed by the Fleurs Synthesis Telescope. Jim Caswell led a number of colleagues in this collaboration. A wide variety of structures in these SNR was observed; the classification into the two classes of shell and filled-centre SNRs remains a useful paradigm today. A noteworthy image of the radio remnant of AD 1006 (G327.6+14.6) was obtained by Caswell, Haynes, Milne and Wellington (1983); with a resolution of 50 arcsec, the 28 arcmin diameter source was well resolved. Detailed comparison

Fig. 4.23 Christiansen (*centre*) talking to delegates visiting Fleurs during the XV International Astronomy Union meeting in 1973. The person on the *left* is Robin Conway of Jodrell Bank in the UK (CSIRO Radio Astronomy Historical Photographic Archives B10256-75)

with optical and X-ray data showed that the images at various wavelengths showed a general, but not detailed, correspondence (e.g. Milne et al., 1985, provided images of 50 SNR using the Fleurs array and the Molonglo Observatory Synthesis Telescope at 843 MHz).

After 1985 (6 years after Chris's retirement), an additional 24 publications from the Fleurs Synthesis Telescope emerged, many under the leadership of John Bunton (the FST ceased operation in 1988 as the Australia Telescope Compact Array came on line). During this 3-year period, two additional 13.7 m antennas were added on the E-W baseline with a total extent of almost 1600 m. (Batty, Bunton, Brown, Corben, & White, 1986; Bunton, Jones, & Brown, 1985). A number of observations were carried out using correlations only between the six 13.7 m antennas, with a resolution of about 25 arcsec.[7] In May 1987, a prominent publication appeared: the first radio detections of the bright supernova 1987A in the Large Magellanic Cloud galaxy with 4 days of the optical outburst. Turtle et al. (1987) detected the radio emission with three instruments in Australia including the six element FST.

Links with China

Chris's interest in China went back to his childhood:

> My interest started in about 1920 through an aunt who was matron of a missionary hospital in China. I later read a book called *Red Star over China*, by Edgar Snow, and became still more interested in China. When I had to go to the IAU meeting in Japan in 1961, I thought, "Why don't I try to get into China?" So I wrote to the Chinese Academy, saying that I was representing our Academy, more or less, at the meeting and asking if they could help me to get a visa to China. Nothing happened for quite a while, and then suddenly they said they would be glad for me to go as their guest, and give lectures and so on. They'd read everything I had ever written, I think. After that, the connection just increased, because while I was there I met the president of their Academy, and I suggested that he ask our Academy to send a delegation to China. A delegation did go, probably in 1964, and in return, a Chinese one came to Australia.

Chris first visited China in 1963. At that stage, an embryonic radio astronomy group was struggling with some copies of Russian solar radiometers. The group was interested in building a solar array but lacked simple things like cables. Chris was able to draw on his earlier experience to help them with open-wire transmission lines. He formed a strong friendship with Wang Shouguan. Wang and Wu Huai-wei visited Sydney in 1964. The group at Fleurs collaborated in the development of the new telescope at Miyun Observatory.

Chris made many visits to China over the years, while Chen Hong-shen and Ren Fang-bin visited Fleurs in 1974. Chris organised lecture tours and visits to the Miyun group by Bob Frater in 1976 and Miller Goss in 1977. In 1979, Chin Kwong visited China as part of that collaboration. Chen Jian-sheng and colleagues also visited Australia in 1979 to observe at Fleurs (Chen, Liang, Cui, & Zou, 1982).

Wang Shouguan has written up the story of the relationship with Chris (Wang, 2009). In recognition of his "long and important contribution to Chinese astronomy", Chris was elected a Foreign Member of the Chinese Academy of Sciences in 1996 (see Fig. 4.24).

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[7] The leaders of this effort at the Sydney University School of Electrical Engineering were John D. Bunton, Michael J. Batty, David R. Brown, I.G. Jones and Julian B. Corben with additional collaborators from the Sydney University School of Physics and the CSIRO Division of Radiophysics.

Fig. 4.24 Christiansen meeting Chou En-lai (Zhou Enlai), the first Premier of the Peoples Republic of China during a visit in 1971 (Courtesy of Christiansen Family Collection)

Local and International Roles in Science

Chris took on significant roles with the international scientific unions. His involvements with both the International Astronomical Union and the International Union for Radio Science began in the 1950s. He served as a vice president of the International Astronomical Union (IAU) from 1964 to 1970, president of the Radio Astronomy Commission of the International Union for Radio Science (URSI) from 1963 to 1966, vice president of URSI 1972 to 1978 and then president from 1978 to 1981. He was appointed a Life Honorary President of URSI in 1984. He was a member of the General Committee of the International Council of Scientific Unions (ICSU) from 1978 to 1981.

In the Australian Academy of Science, to which he was elected in 1959, he was Foreign Secretary 1981–1985, served on the Council for two terms and was chairman of several committees including the National Committee for Radio Science, 1962–1970. He was president of the Astronomical Society of Australia, 1977–1979.

He was a member of the Australia-China Council of Australia's Department of Foreign Affairs, 1979–1982. He was a UNESCO Consultant in India on the construction of a "Giant Equatorial Radiotelescope" in the 1980s.

Chris had extensive scientific linkages, both local and international. He was always looking to involve young engineers and scientists in the work of international bodies. Chris actively recruited young representatives to Academy committees.

His long involvement with both the IAU and URSI, together with his many interactions with peers around the world, gave him an extraordinary international network. This came into play over the years in such things as arranging visits and finding post-doctoral positions.

Chris Christiansen died on 26 April 2007. He is survived by his sons, Steve and Tim. His wife, Elspeth, died in 2001, while their son Peter, an atmospheric scientist at the University of Sussex, died in 1992. Peter was well known to Australian scientists, having spent a sabbatical visit in Sydney in the 1970s.

The Legacy

Those involved with the Fleurs Synthesis Telescope, as staff members or as postgraduate students, learned a lot from the process of developing the instrumentation necessary for an operational telescope. Many have played essential roles in the Division of Radiophysics, in building the Australia Telescope, and even today in the developmental work for the Square Kilometre Array. This success is part of Chris's legacy.

The challenge of the work at Fleurs and the team environment created by Chris yielded other benefits that also stand as his legacy. Key parts of the 802.11 wireless LAN work that led to the formation of the company Radiata that has delivered such handsome royalties to CSIRO were done by people – John O'Sullivan, Graham Daniels, Terry Percival in the patent process and David Skellern in the commercialisation – who went through this system as students.[8] These influences are discussed further in Chap. 8.

In addition to his significant influence in the development of the Westerbork Synthesis Telescope, Chris's influence on the development of radio astronomy in both India (with the links to Govind Swarup) and China (with Wang Shouguan) is inestimable.

Chris truly carried the high status that Australia enjoyed in the early days of radio astronomy through to the present day via the training and experience that derived from the instrumentation at Fleurs. In addition to the PhDs in Electrical Engineering, a smaller number of PhD degrees were awarded in astronomy through the University of Sydney's School of Physics and the Australian National University. Numerous collaborations were established between the University of Sydney (Electrical Engineering and the School of Physics) and other astronomical groups in Australia (CSIRO Division of Radiophysics, Australian National University and the Anglo-Australian Observatory), associations that have continued well into the new century.

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[8] A presentation titled "Rome Wasn't Built in a Day" emphasising the linkages back to Chris's Fleurs vision and the many other significant outcomes that have resulted was published by Matthews and Frater (2003, 2008).

Chris' astronomical legacy consists of two major parts:

1. Major instrumental innovations that had an impact on radio astronomy. Earth-rotational synthesis was achieved in 1955 with the Potts Hill grating array. A few years later, the crossed-grating multi-element interferometer at Fleurs was completed, an instrument based on the twin concepts of the grating array as had been used at Potts Hill and the Mills Cross technique of correlating two orthogonal arrays. After Chris's move to the University of Sydney in 1960, the establishment of a remarkable group in Electrical Engineering led to the Fleurs Synthesis Telescope.
2. New astronomical understanding:
   - (a) The pioneering HI line work in the first years of 21 cm hydrogen spectroscopy, starting in 1951. This work showed the existence of spiral arms in the gaseous component of the Milky Way; the southern galaxy was imaged contemporaneously with imaging of the northern Milky Way by the Leiden group.
   - (b) The determination of the properties of the decimetre sun in the early 1950s at 21 cm (1.4 GHz). At 21 cm, the radiation arises from the transition region between the corona and the outer chromosphere. In this region, the change-over between the steady optical sun and the spectacularly variable metre-wave sun occurs. Thus the determination of the physical conditions in this important region of solar activity. The observations were carried out at Potts Hill using the east-west and north-south grating arrays from 1952 and at Fleurs using the crossed multi-element interferometer starting in 1957, on the first day of the International Geophysical Year. The quiet sun, arising from thermal free-free emission[9] from the solar atmosphere, was investigated in detail, with the detection of the prominent equatorial limb brightening at solar minimum using Potts Hill data from 1953. With the Fleurs array, two-dimensional images were created by scanning the sun during observations of about an hour; the image, with a resolution of about 3 arcmin, was constructed "television fashion" by using scans at different latitudes on the sun. With this method, detailed images of the "slowly varying component" were obtained at a rate of one image per hour.[10] The electron density and temperature (3×10^9 electrons per cubic cm and 2×10^6 K) of the radio regions were determined at elevations of ~ 20,000 km above the sun's surface.

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[9] Radio continuum emission due to the interaction of free electrons with the accompanying protons.

[10] The term "slowly varying component" was invented by J.F. Denisse in 1949 (see Sullivan, 2009, p. 222): "*une composante lentement variable*", slowly varying component. The term (in English) was championed by Christiansen and Pawsey which became the standard terminology within a few years. The slowly varying component arises from a combination of free-free emission and gyro resonance radiation in localised regions of higher electron density and magnetic field at locations above sunspots.

A few years later, during the solar maximum of 1958, the quiet sun was imaged by Labrum (1960) using the Fleurs array. He confirmed the shape of the earlier work from Potts Hill and found that the brightness of the quiet sun emission at the solar maximum was about twice that of the earlier data from Christiansen and Warburton, obtained during the previous solar minimum.

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Chapter 5
Paul Wild: Radio Astronomy and the Sun

John Paul Wild (see Fig. 5.1) was born on 17 May 1923 in Sheffield, England, the son of cutlery manufacturer Alwyn Wild and Bessie Wild. He was one of four sons: Arnold, followed by Mark, Ted and then Paul. In an interview late in life, Paul remembered (Moyal, 1994):

> My father was a cutlery manufacturer living in a rather grand house with, I think, three cars including a Rolls and a Daimler and something else. However, just about the time I was born, which was 1923, there was a depression and he went bust. And when I was 3 months old he left the country to go to America in an attempt to sell his patents and so on for cutlery manufacture, and in the event he never returned. I met him eventually when I was 33 years old.

Paul's family moved to Croydon, south of London, and, as Paul described it, went from riches to rags. At the age of six, he got off a train and was run over by a lorry. He spent 6 months in the hospital with a fractured skull but recovered completely. After an unhappy spell in boarding school, Paul attended a local preparatory school and then the Whitgift School in Croydon.

The gift of a Hornby train from his mother when Paul was 7 years old started his lifelong love of trains. The locomotive had "Great Western" written on it, and it started him on a study of the history of the Great Western Railway. He also read about the railways and extraordinary ships that the famous British engineer Isambard Kingdom Brunel FRS built and claimed Brunel as his first source of inspiration.

Paul visited Southampton many times to see and take photographs of the ships he loved. He was particularly interested in the big ocean liners, such as *Queen Mary*. Sometimes his brother Ted would row him out in a small dinghy so that Paul could take better, closer photographs.

Paul described three ambitions when he was 7 years old: to be a train driver on a King Class locomotive, to be an opening batsman for Yorkshire and to become a Fellow of the Royal Society. As he said, "I was happy I achieved one of these".

R.H. Frater et al., *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, Astronomers' Universe, DOI 10.1007/978-3-319-65599-4_5

Fig. 5.1 Paul Wild in 1969 (CSIRO Radio Astronomy Historical Photographic Archives B9107-5)

Paul had an early love of mathematics and attributed much to his analysis, calculus and modern geometry teachers. With this came a "little bit of physics and current affairs" and leisure times devoted to bridge. He went to Cambridge in 1942:

> And the first year I did Mathematics Part 1, Mathematical Tripos Part 1, but I could only stay on at the time without going into war service if I did something more useful to the national war effort. So that's how I became a physicist. I went straight into Part 2 Physics, which is fairly tricky because the great majority of people had already done 2 years of it before, so it was a real challenge. But I enjoyed it very much, and I was very inspired by the sort of grandeur of the approach, the wonders of quantum mechanics and relativity and that kind of thing. It was hard work, it was 6 days a week.
>
> In the event, I left after the second year and had the choice of joining one of the three services, or going to research, radar research, or industry. And I joined the navy, because I'd always had a great interest in ships and the sea in general. It turned out, since I went up one term late when I went to Cambridge, that I only spent five terms at a university, and I've only spent five terms in my life at a university. After a year away, they gave you a wartime degree, which was a Bachelor of Arts. But a few years later, one paid £5 and it became a Master of Arts. That's the way things happen at Cambridge. And after 10 years of research, I collected a whole lot of papers up and sent them to Cambridge and, after a 2-year deliberation, they gave me a Doctor of Science at Cambridge. And that's my very limited university career (Moyal, 1994).

Wartime

Paul joined the navy in July 1943 as a Probationary Temporary Acting Sub-lieutenant (Special Branch RNVR). He did a 6-month training course at Portsmouth as a radar officer, drawing on a special radio course he had done at Cambridge. Paul became assistant, then senior radar officer on the flagship *HMS King George V*. The ship was part of Task Force 57 that served in the Pacific. Paul spent the next two-and-a-half years in that role, being promoted to lieutenant. Before setting sail for the Pacific, the *King George V* was in Scotland where it was visited by King George VI, Queen Elizabeth and Princesses Elizabeth and Margaret. Paul spoke of making his name by responding to a question from the Admiral at a critical moment that "normal" meant "at right angles to" and then Wild watched the radar in amazement as the whole fleet turned through 90°.

Sydney was the rear base for Britain's Pacific fleet, and it was during his many visits to Sydney that Paul met Elaine Hull, giving him a good reason to come to Australia. The two corresponded frequently after Paul returned to England at the end of the war. He proposed to Elaine, sending a ring by mail.

In England Paul taught radar to naval officers until, in 1947, he obtained a job at the Radiophysics Laboratory of CSIR in Sydney. He would be developing and maintaining test equipment.

After a year in this role, he went into radio astronomy research with Joe Pawsey's group. Paul was a great admirer of Pawsey: "He just provided ideal conditions, an ideal environment to allow everyone to use their own initiative". Pawsey gave him the option of joining a colleague, John Bolton, to do work on radio sources or to join another colleague, Lindsay McCready, to build a solar spectrograph. Paul saw that he would be very much a second-in-command with John Bolton. If he joined McCready he would be able to do his own thing. As he said: "And that's why I became a solar man".

Solar Spectral Work at Penrith and Dapto

In his then-role as an assistant research officer, Paul started his work in solar radio astronomy, working with McCready to build a spectrograph to study solar bursts. They set up a very crude field station with a couple of trailers and the antenna, not far from the railway line at Penrith Station at the foot of the Blue Mountains outside Sydney (see Figs. 5.2 and 5.3). It was a very sparsely populated area in those days, so there was a reasonably low radio noise level. As Paul described it:

> Then one just waited until something happened. Every now and then a great burst would come from the sun and we were very excited and we photographed everything that went on with a movie camera. After 4 months we got so much data that we just closed everything down and came back, and I analysed the data at very great length; the results were spectacular (Moyal, 1994).

Fig. 5.2 The rhombic aerial in May 1950 used by Wild at Penrith field station west of Sydney for detecting the solar radio emission from 70 to 130 MHz. A series of guide ropes were used to point the aerial at the sun as it pivoted on its base. From these initial observations, in a ground-breaking paper based on their time and frequency behaviour, Wild proposed the classification of solar bursts into three main Types I, II and III, which are still used today (CSIRO Radio Astronomy Historical Photographic Archives B2086-1)

This instrument, for the first time, allowed a display of frequency versus time (i.e. dynamic spectra) covering a swept-frequency range from 40 to 70 MHz (see Fig. 5.4). Wild and McCready identified and named three types of bursts – Types I, II and III, distinguished by the way the frequency drifted with

Fig. 5.3 Paul Wild (*centre*) at the Penrith field station in 1950 with the equipment trailers in the background. Keith Macalister is kneeling on the *right*. The base of the rhombic aerial is visible on the *right* of the image (CSIRO Radio Astronomy Historical Photographic Archives B8792-3)

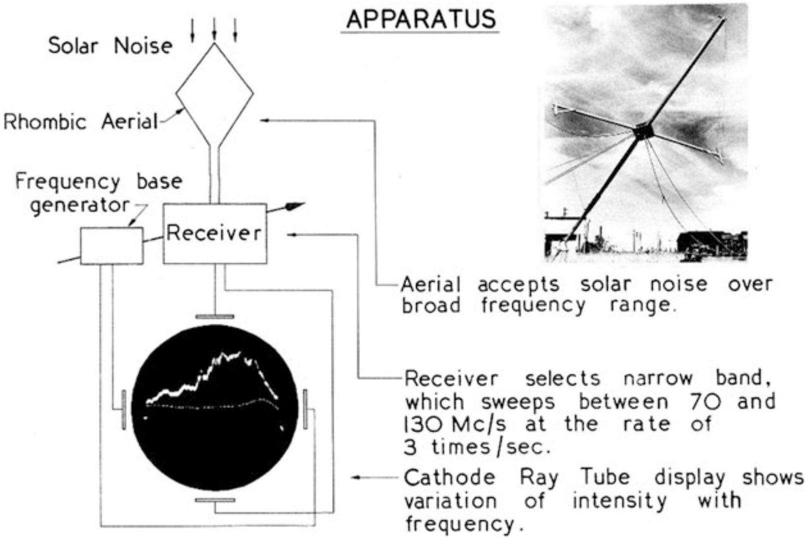

Fig. 5.4 A poster explaining the operation of the swept-frequency rhombic aerial and receiver prepared for the 1952 URSI General Assembly held in Sydney (CSIRO Radio Astronomy Historical Photographic Archives B2222-30)

time – and published a series of papers in 1950 that became the foundations for all future work on solar bursts. They deduced that the Type II bursts were associated with shock waves coming out through the solar atmosphere at 1000 km/s and were associated, 30 h later, with aurorae in the earth's night sky. They associated Type III bursts with streams of electrons being ejected at a third the speed of light and taking only an hour to reach the earth. The mechanisms proved to be correct and their nomenclature for the phenomena became the international standard.

In 1954, Paul was joined by electrical engineer John Murray (see Fig. 5.5) and technician William Rowe to build a more sophisticated dynamic spectrograph on a

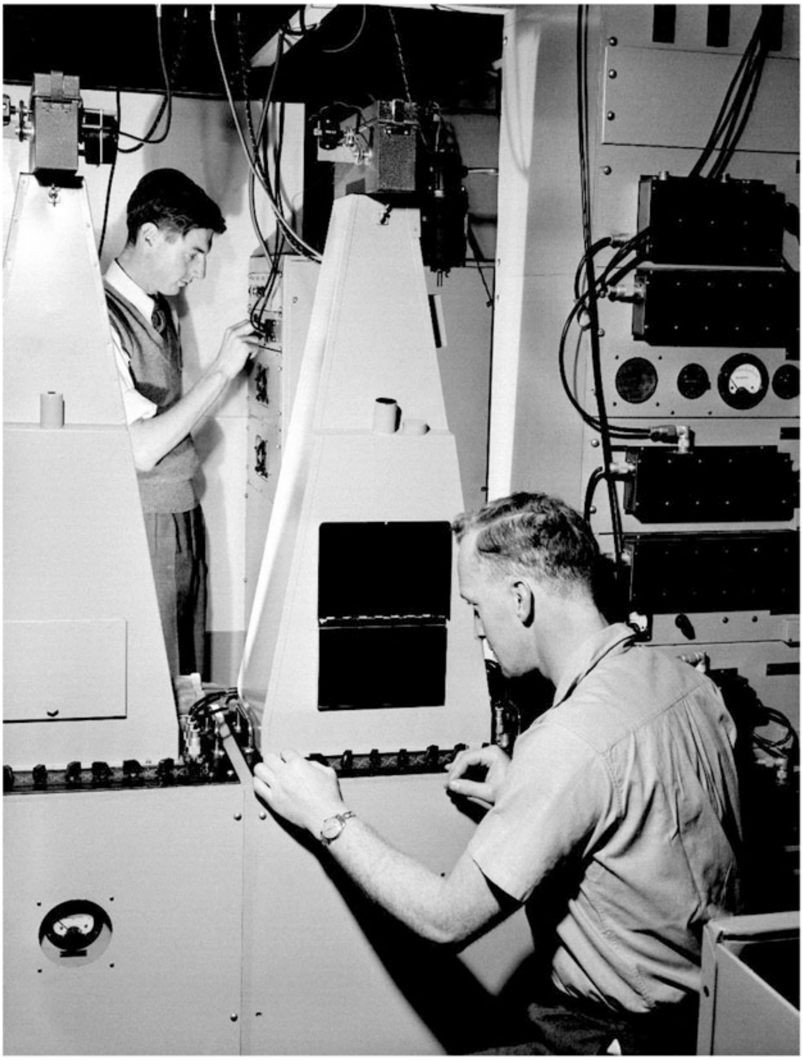

Fig. 5.5 Wild (*left*) and John Murray adjusting one of the two solar spectrograph displays at Dapto field station in August 1952. The radio spectrograph produced two solar spectra per second over a frequency range originally of 40–120 MHz and later extended to 5–2000 MHz. Until 1957 this was the only radio spectrograph operating in the world (CSIRO Radio Astronomy Historical Photographic Archives 2833-4)

Fig. 5.6 Two of the three crossed-rhombic aerials in final stages of construction at Dapto field station, near Wollongong in November 1951. Each aerial is equatorially mounted to track the sun and operated in three bands, 40–75, 75–140 and 140–240 MHz. In the background is the receiver hut. The spectrographs became operational in August of 1952 (CSIRO Radio Astronomy Historical Photographic Archives B2640-5)

dairy farm at Dapto, 100 km south of Sydney (see Figs. 5.6, 5.7, 5.8 and 5.9). The site was chosen because of its lack of man-made radio frequency interference. Three rhombic antennas covered a frequency range from 40 to 240 MHz. The first results were presented at the 1952 URSI General Assembly in Sydney (Sullivan 2009). The earlier results were confirmed and extended over the next decade. The dynamic spectra showed the way the complex frequency structure in the solar radio emission varied with time (frequency sweep). A slanting band in these 2-D displays indicated a continuous variation in the burst frequency with time (see Figs. 5.10 and 5.11).

Fig. 5.7 The three completed cross-rhombic aerials of the solar spectrograph at Dapto field station in September 1952 (CSIRO Radio Astronomy Historical Photographic Archives B2888-2)

Paul described the work (Bhathal, 1996):

> Through a long series of observations involving high-precision directional observations, as well as frequency-sweep, plus a lot of theory, we were able to prove the meaning of these slanting bands. Around the sun is a huge atmosphere (the corona, seen only at total eclipses) of ionised gas. This is where the radio waves originate: different frequencies originate at different levels, high frequencies closer to the sun's visible surface, lower frequencies further away. This meant that the slanting bands were due to the source of radiation *moving outwards through the solar atmosphere*. With the aid of models based on eclipse data, we were able to work out the height in the solar atmosphere corresponding to each frequency; and so from the slant of the bands we could work out the speed at which the source was ascending. It turned out that the speeds fell into two very distinct categories. One was around 1000 kilometres per second (km/s); the other at least a hundred times faster, or about one-third the speed of light.

Nothing had ever been seen to move on the sun at such high speed, and this interpretation was inevitably met with considerable scepticism (Sullivan, 2009).

Fig. 5.8 Paul (*centre*) and Kevin Sheridan (*right*) doing maintenance work at the Dapto field station (CSIRO Radio Astronomy Historical Photographic Archives P13114-9)

Paul likened this research to the study of taxonomy that preceded Darwin's "On the Origin of Species". His analysis of the anatomy of the solar flares and his development of the physical interpretation culminated in a unified model that integrated the apparently complex radio flare phenomena in the solar chromosphere, the solar corona and the interplanetary space. The phenomena of Type II and Type III bursts, especially the latter because of their simple structure, stimulated a great deal of interest among theoretical physicists and, in particular, plasma physicists.

After 10 years of research, Paul's collected papers gained him a Doctor of Science degree from Cambridge. The Sydney group was the pre-eminent group in the world for solar radio astronomy and would continue their work for three decades (see Figs. 5.12, 5.13, 5.14, 5.15, 5.16, 5.17 and 5.18).

Ionospheric Scintillation

A sunspot minimum occurred in 1955, not many years after the Dapto solar radio spectrograph commenced operation. In this period, solar observations were only recorded occasionally when sunspots were visible. Paul used the resulting availability of equipment and manpower to study the ionospheric intensity scintillations. He was joined by Jim Roberts, and they confirmed previous findings that

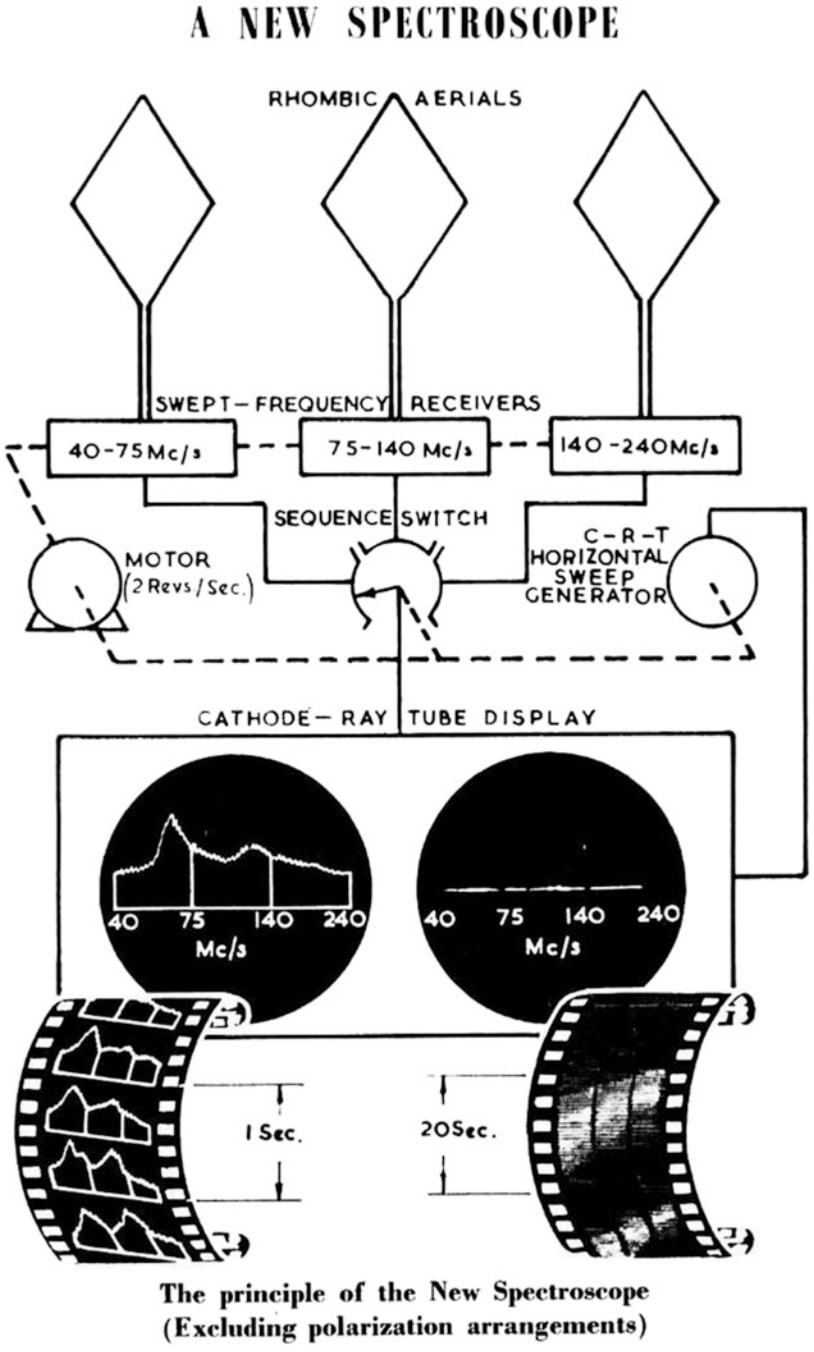

Fig. 5.9 A schematic diagram of the Dapto spectrograph. This spectrograph had an increased frequency coverage in three bands (40–240 MHz). Two displays were used. The one on the *left* was similar to the Penrith instrument with frequency displayed along the *horizontal axis* and

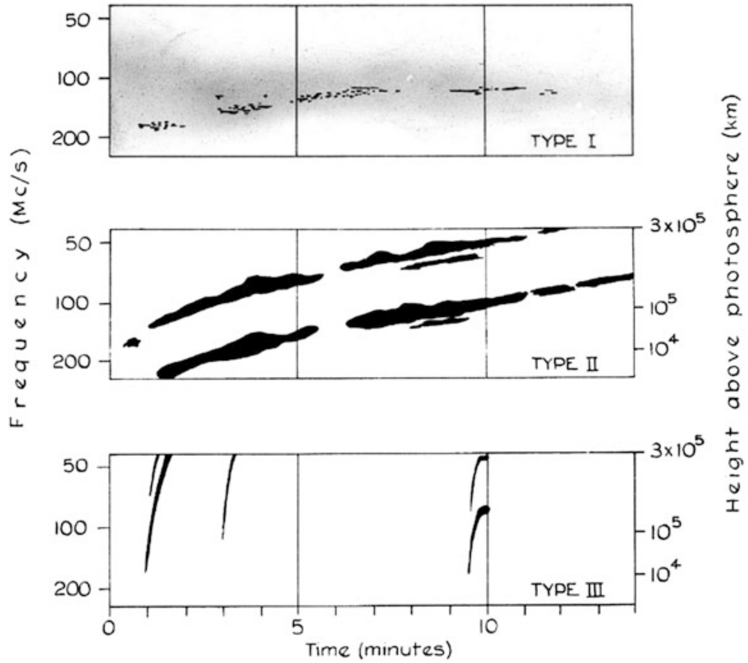

Fig. 5.10 A schematic diagram illustrating typical spectral feature of Type I, II and III solar bursts. In the case of both the Type II and III bursts, the second harmonics of the burst are displayed. The Type II bursts inferred an outward velocity in the order of 700 km/s and are associated a day later with aurora on earth. Type III burst velocities are up to 30,000 km/s. Type II bursts occur over timescales of minutes, whereas Type III burst occurs over seconds. Type I bursts do not show a clear frequency drift with time. The frequency drift can be interpreted as a velocity using an assumed electron density model of the corona. A decreasing electron density at greater heights than close to the photosphere (CSIRO Radio Astronomy Historical Photographic Archives B3685-4)

the scintillations resulted from relatively stable spatial patterns of intensity with scale sizes of the order of 10 km drifting across the ground at speeds of the order of 100 m/s. Two new results were that the patterns on the ground were elongated and that the ionospheric irregularities causing the daytime scintillations were located in the E-layer, while those causing the night-time scintillations were in the F-layer. This latter result was the subject of a paper in *Nature* (Wild & Roberts, 1956).

Fig. 5.9 (continued) intensity along the *vertical axis*. The second display was similar with frequency on the *horizontal axis*, but in this case intensity was modulated as the cathode ray tube beam was swept horizontally across the screen. This was used for continuous film recording and was much more efficient than recording individual images of the *left-hand side* display (CSIRO Radio Astronomy Historical Photographic Archives B3686)

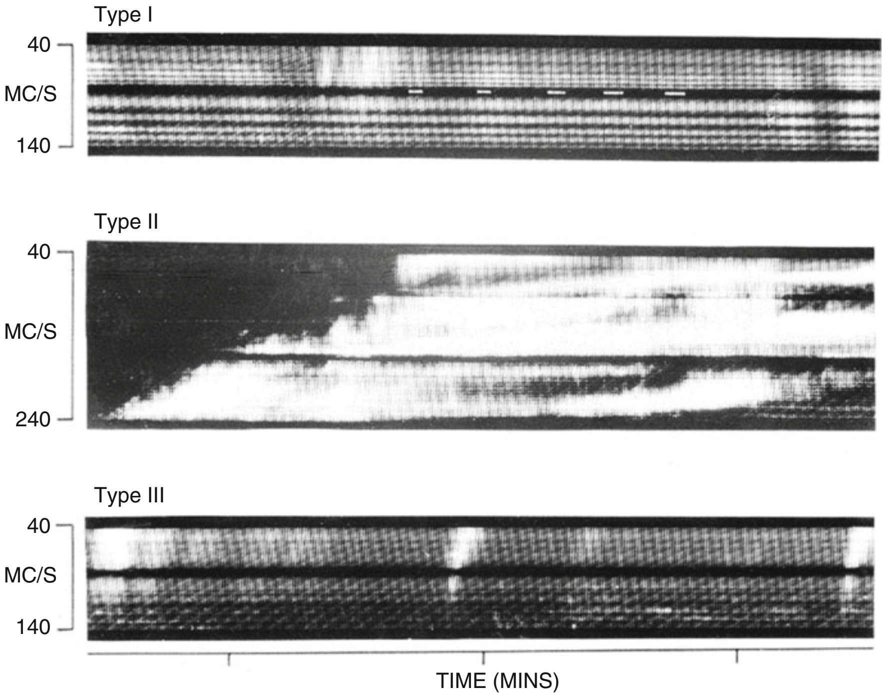

Fig. 5.11 Actual spectrograms of the three main types of solar bursts taken using the Dapto spectrograph. Note that the Type I burst example also contains a faint cluster of Type III bursts (CSIRO Radio Astronomy Historical Photographic Archives B3685-10)

Paul measured the dynamic spectra for the first time, and he realised that the observed scintillations must be produced by the focusing effect of large refracting elements in the ionosphere. If contributions were received from many small refracting elements, then the features would be narrowband and dispersed randomly in the time-frequency plane, and this was only occasionally observed. This interpretation was counter to the prevailing theory, based on the diffractive scattering caused by small-scale irregularities that had been developed in the Cambridge group. Because of this disagreement in interpretation, Paul's work received very little recognition at the time. Not until 1975 was the full theory of scattering by a power-law spectrum worked out by Gochelashvily and Shishov (Prokhorov, Bunkin, Gochelashvily, & Shishov, 1975). This made it clear that the diffractive scintillations described by the Cambridge model were modulated by the refractive scintillations that had already been seen so clearly in the dynamic spectra of Wild and Roberts taken 20 years earlier. This power-law model has now been successful in describing scintillations in the ionosphere, the solar wind and the interstellar plasma. Had Paul's demonstration of the importance of refractive effects been accepted at the time, scintillation theory would have advanced much more rapidly.

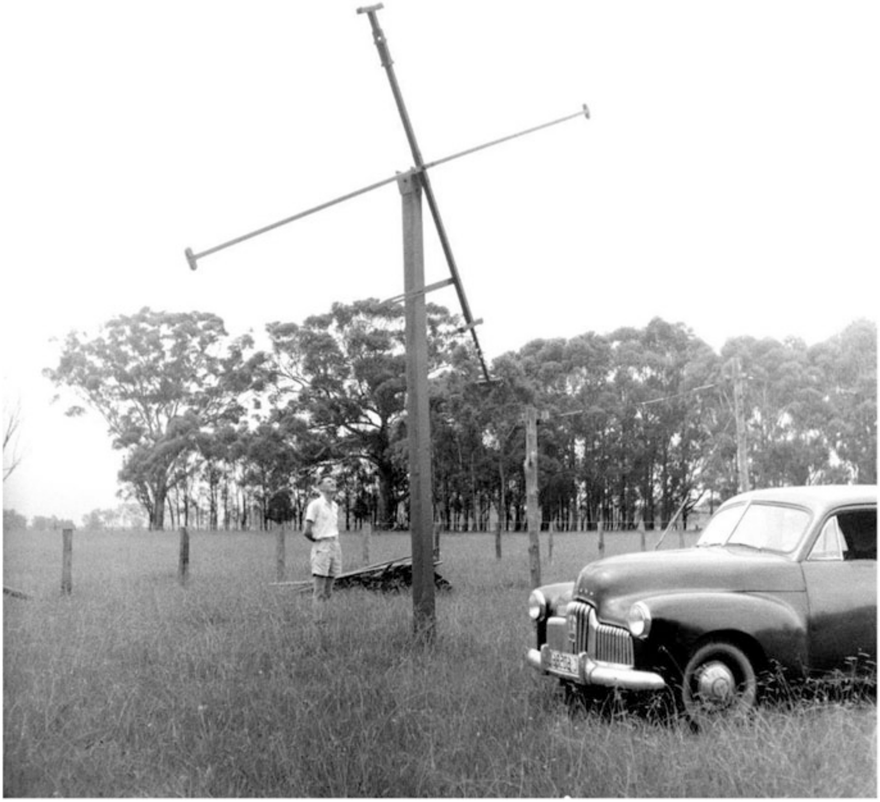

Fig. 5.12 Wild standing next to one of the swept-frequency interferometer rhombic aerials at Dapto field station in March 1955. The open wire transmission lines are visible on the post on the right on the image. Two aerials were arranged on an east-west baseline 1 km apart, with a second pair of aerials at a shorter baseline of 0.25 km used to assist in accurate lobe identification. In the late 1950s, the swept-frequency interferometer was extended to a swept-lobe interferometer (CSIRO Radio Astronomy Historical Photographic Archives 3590-2)

The Hydrogen Line and the Zeeman Effect

In the course of this solar work, Paul began to suspect that there were spectral lines in the solar burst they were observing and became interested in the radio spectrum of hydrogen. He wrote an internal report related to the potential for spectral lines in the solar bursts. When "Doc" Ewen and Ed Purcell at Harvard in the USA first detected the 1420 MHz (21 cm) hydrogen line transition in the interstellar medium in 1951, Paul went back to his report, generalised it to include the hyperfine

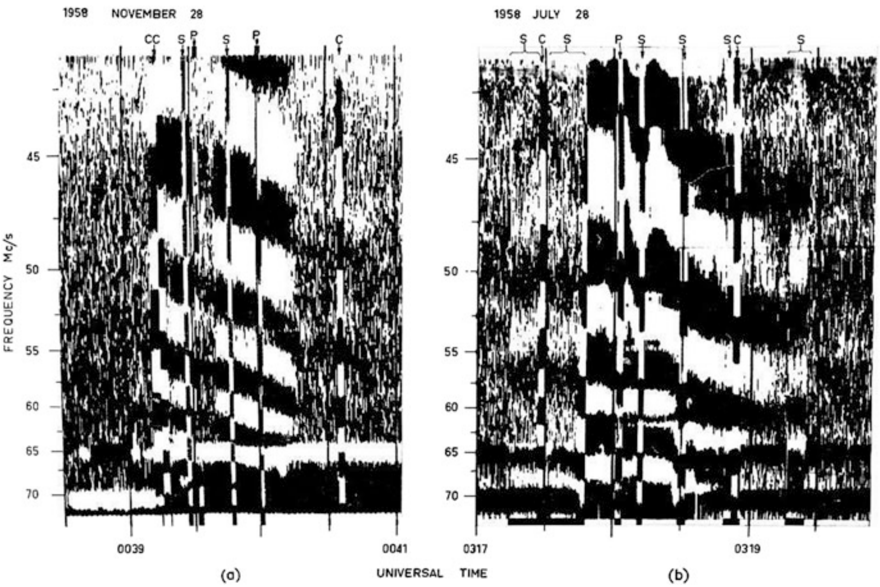

Fig. 5.13 An example record of Type III solar bursts obtained from the swept-frequency interferometer. The output was recorded on a paper facsimile recorder with each vertical line representing a simple time slice recording. The basic interference pattern is obtained from a 1 km aerial baseline. The distinct strips marked (S) record short periods when a 0.25 km baseline was used. The (P) indicates when the system was switched to the polarisation aerial system and (C) when calibration markers were introduced. The example marked (**a**) shows a source moving at a fairly constant position and hence the constant slope of the interference pattern. The record on the *right* marked (**b**) shows an example of a source undergoing a rapid change in position and hence the changing slope. The *horizontal* bands visible between 65 and 70 MHz are due to interference from television stations (CSIRO Radio Astronomy Historical Photographic Archives B5864-7)

structure of hydrogen and 6 months later published the first detailed theoretical paper (Wild, 1952) on the hydrogen lines – a classic in the field.

One of the powerful tools in modern astronomy is the use of the Zeeman effect[1] to make a direct measurement of the strength of the magnetic field in astronomical sources by measuring the slight shift in the frequency of spectral lines. Paul played a key role in the recognition that the 21 cm hydrogen line could be used to measure this Zeeman effect as he describes in his biographical memoir of John Bolton (Wild, 1994):

> On a visit to Caltech in 1957, I spent a day at Mount Wilson Observatory and watched Babcock measure solar magnetic fields by observing the split of spectral lines by the Zeeman effect. Next day I made the long drive to the Owens Valley Radio Observatory with John Bolton. I said, “I wonder if it would be possible to measure galactic magnetic

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[1] Zeeman effect: splitting a spectral line into several components in the presence of a static magnetic field.

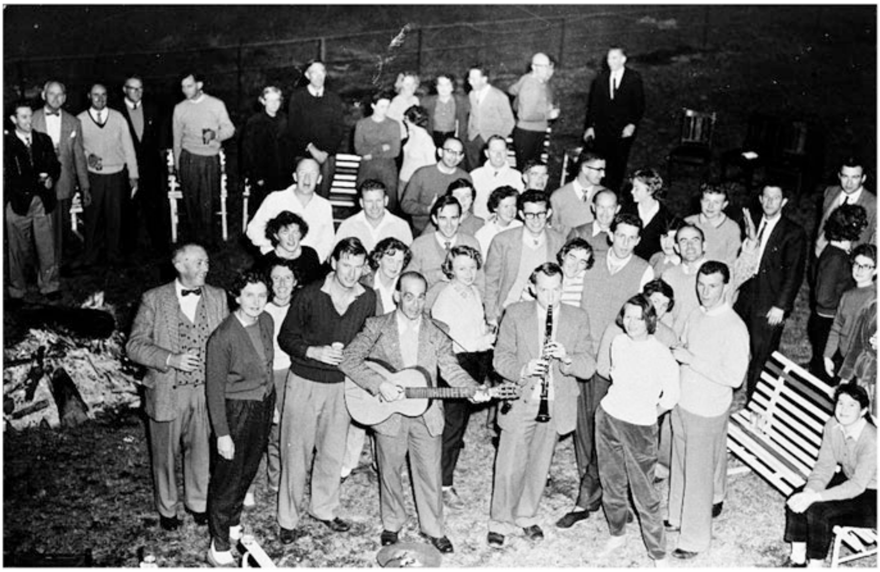

Fig. 5.14 A mid-year Radiophysics party at Dapto field station in July 1959. The guitar player is Steve Smerd. To the immediate left is Wild and his wife Elaine. Playing the clarinet is Gil Bogle from the National Standards Laboratory. Joe Pawsey (in *black*) is standing in the *back row* behind Wild to the *centre left* and with his wife Lenore (also in *black*) (CSIRO Radio Astronomy Historical Photographic Archives B5865)

Fig. 5.15 Paul Wild (*centre*) visiting John and Letty Bolton at Laguna, California, USA, in September 1959 while Bolton was at Caltech (CSIRO Radio Astronomy Historical Photographic Archives Owens Valley (courtesy of Jim Roberts)

Fig. 5.16 The broadband 200–2000 MHz 30 f. parabolic aerial on an equatorial mount located alongside the three rhombic aerials at Dapto. This new instrument was used to extend the frequency coverage of solar burst analysis (CSIRO Radio Astronomy Historical Photographic Archives B7516-10)

fields by observing the Zeeman splitting of the hydrogen line". We talked about it, exchanging ideas in an exhilarating conversation throughout the drive. Next day I wrote the Bolton and Wild paper that incorporated the ideas of both of us. This paper (Bolton & Wild, 1957) started a prolonged search in a number of observatories and was eventually successful.

Fig. 5.17 Dapto field station showing the 200–2000 MHz parabolic aerial together with the three original rhombic aerials (CSIRO Radio Astronomy Historical Photographic Archives P10478-2)

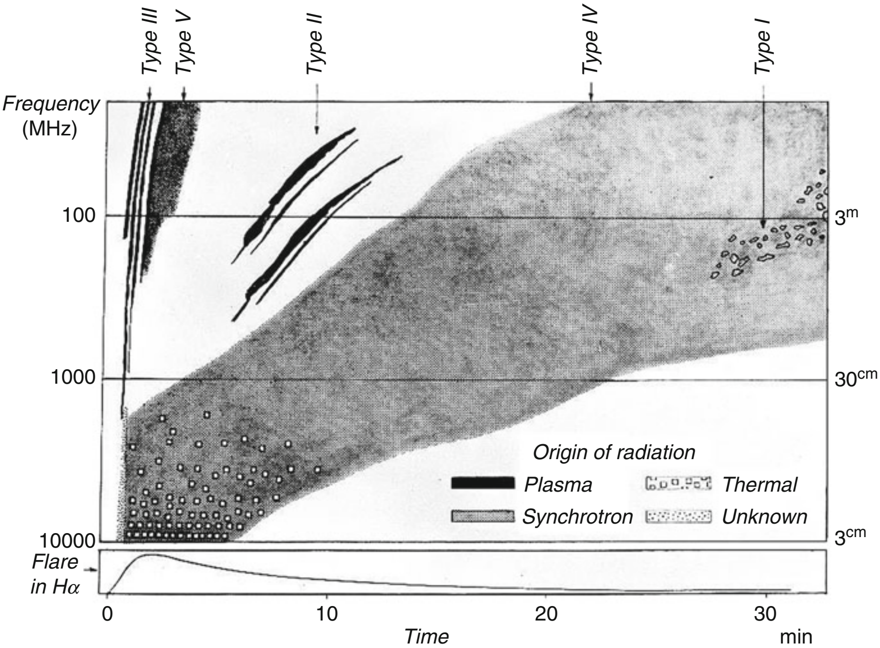

Fig. 5.18 A diagram illustrating the solar radio burst types following a solar flare together with the origin of the mechanism producing the radiation (CSIRO Radio Astronomy Historical Photographic Archives B7456)

Zeeman-splitting observations of the 21 cm line and other radio lines have become the key to our understanding of magnetic fields in our galaxy with some 400 papers now published on this topic.

The Radioheliograph

All the results from Paul's group had been inferred from the spectral observations, and there was a growing desire to be able to image the sun at the same range of frequencies with angular resolution comparable to the human eye. In other words, they now wanted to get a moving picture of the phenomena on the sun. This was a formidable challenge that dictated the need for an instrument more than a million times the size of the aperture of the human eye – that is, 3 km across. The first formal proposal for such an imaging instrument was put forward by Paul in June 1959. At this stage, he envisaged a crossed-grating instrument of the type used by his Radiophysics colleague Chris Christiansen. He sought two modes, one where pictures would be formed in seconds and another where perhaps one picture per hour would be made.

As the proposal evolved, it became the only project, other than the construction of the Parkes 64 m telescope that would be carried out in CSIRO's Division of Radiophysics. Proposals from two other senior members of the Division, Bernie Mills and Chris Christiansen, were not supported, and they left the Division to take up roles at the University of Sydney.

As Paul developed his proposal, he rejected the cross structure because of potential side lobe problems. He devised, instead, a unique beam-forming method using an annular structure with 96 antennas on a circle 3 km in diameter (see Fig. 5.19). This would behave like a filled dish 3 km in diameter. The fast image generation needed to make a moving two-dimensional image of the sun exceeded the computational capability of contemporary computers, and Paul invented a new image processing technique called J^2 synthesis which used the real-time electronic summation of Bessel functions[2] to solve this problem.

With Pawsey's help, $630,000 was raised from the Ford Foundation in the USA to build the radioheliograph. Originally, the plan was to locate it at Parkes. However, the area required (3 km by 3 km) was too large to be accommodated at Parkes, so a more suitable site was found on the northwest plains of New South Wales at Culgoora (see Fig. 5.20), near the town of Narrabri, some 600 km from Sydney (Haynes et al. 1996).

Paul's friend Kevin Sheridan (see Fig. 5.21), chief electronics engineer at CSIRO, was the key figure in the development of the radioheliograph (see Figs. 5.22, 5.23, 5.24, 5.25, 5.26, 5.27, 5.28, 5.29, 5.30 and 5.31). The instrument was completed and

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[2] Special mathematical functions with applications to physical optics. The common notation for the function is the letter "J".

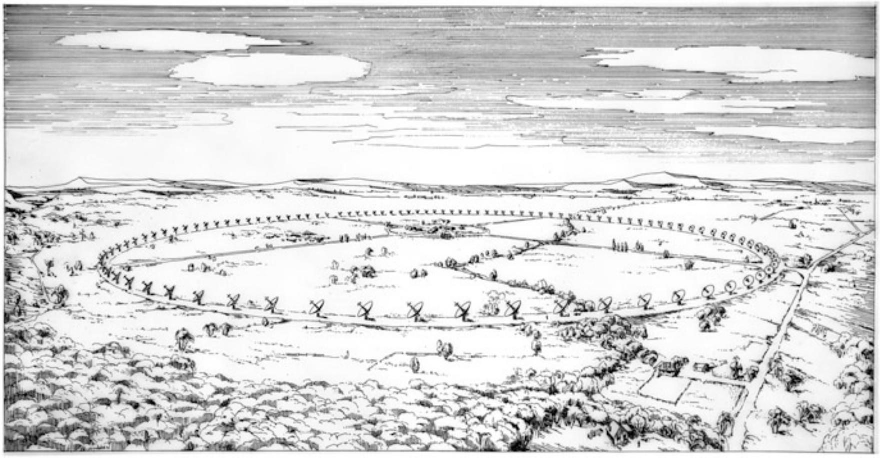

Fig. 5.19 An artist's impression of the Culgoora radioheliograph. It shows the intended 96 dishes, each a 13.7 m dish equatorially mounted in a circle 3 km in diameter (CSIRO Radio Astronomy Historical Photographic Archives B6636-22A)

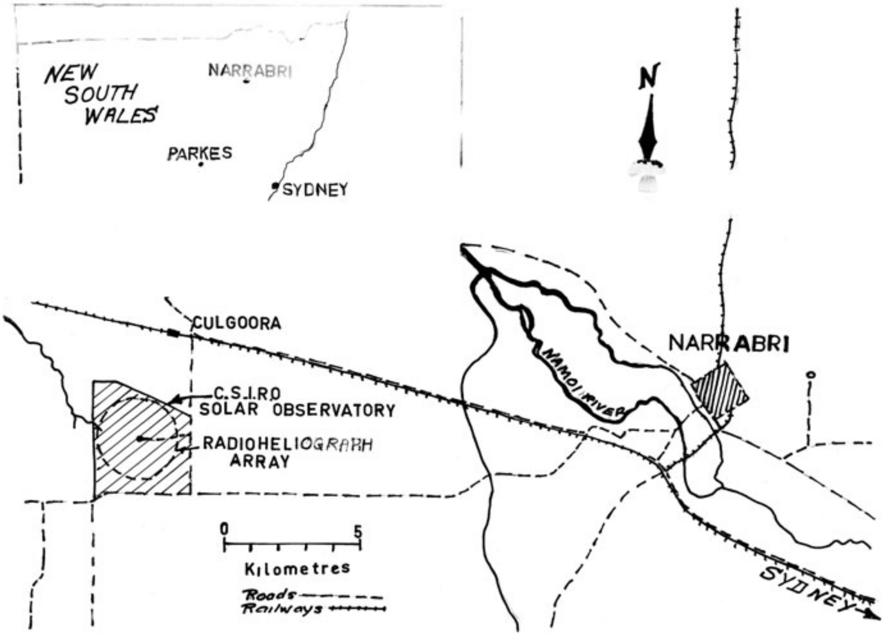

Fig. 5.20 A map showing the location of radioheliograph at Culgoora, NSW, to the west of the northern NSW town of Narrabri (CSIRO Radio Astronomy Historical Photographic Archives B8677)

Fig. 5.21 Kevin Sheridan with the receiver equipment at Culgoora in 1971 (CSIRO Radio Astronomy Historical Photographic Archives N9626-21)

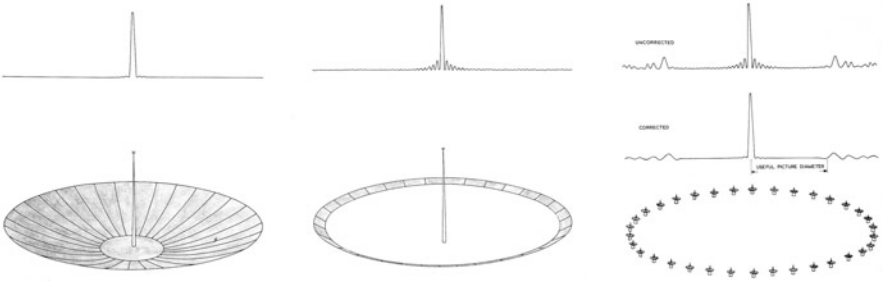

Fig. 5.22 A diagram showing the different aerial beam response patterns. On the *left* is a typical parabolic reflector. Constructing a 3 km diameter reflector is impractical. The *central* image shows a ring configuration which would require a very high and accurately placed central tower at the focal point. The *right* image shows a ring of small dishes. This is much simpler to construct, and by using a correction algorithm, the troublesome side lobes can virtually be eliminated (CSIRO Radio Astronomy Historical Photographic Archives B6636-11A)

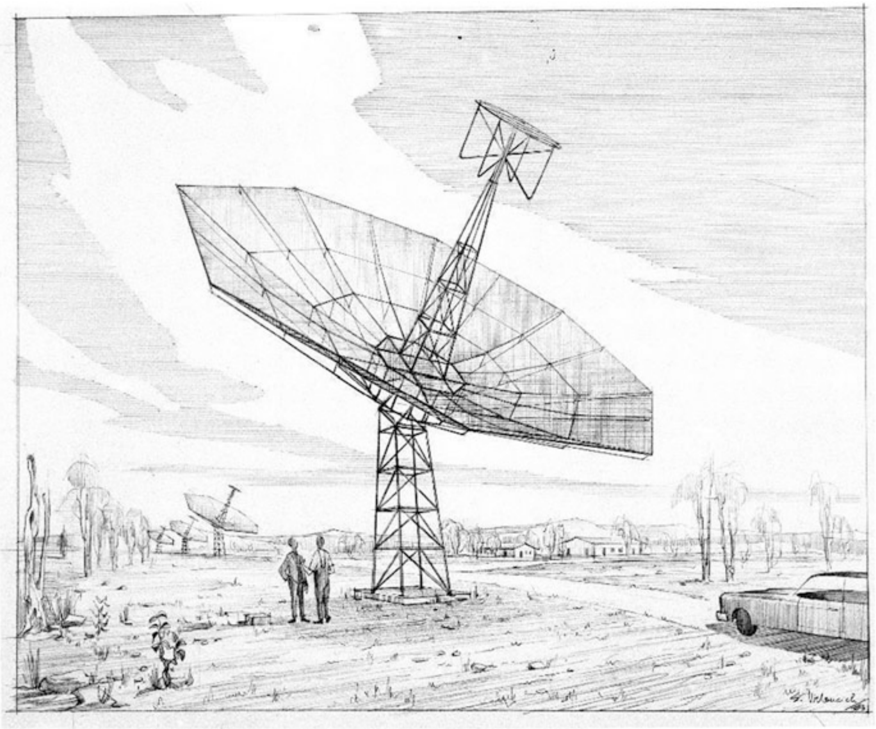

Fig. 5.23 An artist's sketch of one of the 96 proposed aerials for the Culgoora radioheliograph (CSIRO Radio Astronomy Historical Photographic Archives B7035)

commenced operation in 1967. It could produce dual-polarisation radio pictures of the sun at a rate of one two-dimensional image per second and normally cycled through four observing frequencies: 327, 160, 80 and 43 MHz. Paul's own description captures the performance of the instrument:

> It was a hell of a business getting it right, getting all the phasing and so on, and it took quite a team of us, after building it, a couple of months or more getting it to work. When it did work, it worked beautifully, and we photographed these solar phenomena in two senses of circular polarisation and ultimately displayed this as a colour picture, red being right-handed and blue being left-handed polarisation. The pictures were very spectacular and showed all manner of phenomena. It showed what the different types of bursts looked like. Type III were little spikes, little concentrations of light, whereas for the Type II, you could actually see the great shock waves propagating across the sun (Frater, 1982).

The two-dimensional moving images from the radioheliograph provided very important details on the evolution of the Type II and Type III bursts, but for the Type IV[3] bursts, it gave a completely new picture. One could also see for the first

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[3] Of the five main spectral types of solar radio bursts, the Type IV was the only one not introduced by Wild's group. This classification came from a prominent solar physicist in France, A. Boischot, in 1957.

Fig. 5.24 A full-scale prototype of one of the radioheliograph aerials undergoing testing in 1963 (CSIRO Radio Astronomy Historical Photographic Archives B7268-2)

time that they were not all the same but included a lot of different phenomena with great loop structures associated with giant magnetic fields and sometimes polarised blobs that moved out to a great distance (Sullivan, 1978). They would take perhaps half an hour to travel out to distances up to six or more solar radii. What this did, in a way, was to increase the size of the observable sun by a factor of six in radius. Another early exciting discovery was that there were bursts that were not all coming

Fig. 5.25 Fabricating one of the 96 aerials of the radioheliograph on site at Culgoora in 1964 (CSIRO Radio Astronomy Historical Photographic Archives B7354-10)

from the same centre, as had previously been assumed. Two active centres, separated on the sun's surface by as much as a million kilometres, appeared nearly simultaneously as if they could move faster than the speed of light. In reality, an event deeper in the sun was triggering both bursts.

The heliograph stayed in operation for 17 years from 1967, providing a wealth of new information and new insights into phenomena of the solar corona and the relationship between solar and terrestrial phenomena.[4] Paul published 30 papers on the design and research with the instrument (see Figs. 5.32, 5.33, 5.34 and 5.35). The

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[4] Prominent examples that Paul Wild presented at the International Astronomical Union General Assembly in Sydney in 1973 were (1) the size of the sources of metre wave solar bursts and the associated intensities, (2) the opposite polarisation of emission from the two footpoints of the radio emission associated with sunspots, (3) the apparent source heights and the importance of scattering and ducting due to the solar corona, (4) radio evidence on the coronal magnetic field and (5) radio evidence on coronal mass ejections.

Fig. 5.26 The radioheliograph aerials laid out ready for mounting at Culgoora in 1964 (CSIRO Radio Astronomy Historical Photographic Archives B7515-22)

remarkable contribution of the radioheliograph was summarised in *Solar Radiophysics: Studies of Emission from the Sun at Metre Wavelengths*, a book edited by his colleagues McLean and Labrum (1985) to which Paul contributed the introductory chapter, “The beginnings [of solar radiophysics]”.

In an address to the IAU General Assembly in Sydney in 1973, Paul remarked:

> I have the feeling that, to most astronomers, the sun is rather a nuisance. The reasons are quite complex. In the first place the sun at once halves the astronomer’s observing time from 24 to 12 h, and then during most of the rest of the time it continues its perversity by illuminating the moon. Furthermore I have met numerous astronomers who regard solar astronomy to be now, as always before, in a permanent state of decline—rather like Viennese music or English cricket. Nevertheless, those who study the sun and its planetary system occasionally make significant contributions. There were, for instance, Galileo and Newton who gave us mechanics and gravitation, Fraunhofer who gave us atomic spectra, Eddington and Bethe who pointed the way to nuclear energy, and Alfvén who gave us magneto-hydrodynamics. Perhaps the point to be recognized is that the sun has more immediately to offer to physics than to astronomy.

Fig. 5.27 The radioheliograph aerials following assembly on their mounts (CSIRO Radio Astronomy Historical Photographic Archives B7515-26)

Astronomical Society of Australia (ASA)

In 1966 Paul was one of the driving forces behind the founding of the Astronomical Society of Australia. He chaired the inaugural meeting in November 1966. In his opening address, Dr. R. G. Giovanelli likened the emergence of the Society to the build-up of a signal amidst noise, and he linked the names of Buscombe, Gascoigne, Giovanelli and Wild to the generation of the first signal (PASA, 1967). Paul was one of the first vice presidents of ASA and was also the editor of the Society's new Australian astronomy journal, *Proceedings of the Astronomical Society of Australia*, for its first 2 years.

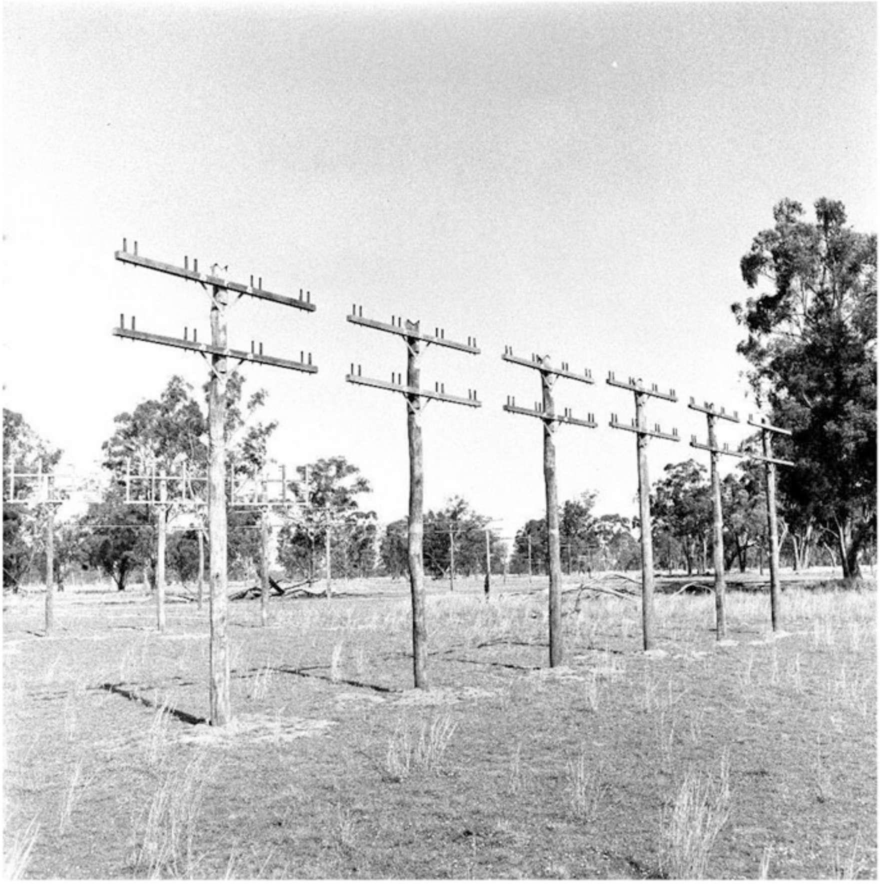


Fig. 5.28 The pole carrying the transmission line of the radioheliograph at Culgoora (CSIRO Radio Astronomy Historical Photographic Archives B7660-3)

Chief of Radiophysics

Edward “Taffy” Bowen had been Chief of CSIRO’s Division of Radiophysics since the end of the World War II. Paul, who succeeded Bowen as Chief in 1971, had this interesting analysis of his predecessor (Hanbury-Brown, Minnett, & White, 1992):

> I was one of several young research scientists who joined the CSIR Radiophysics Laboratory in the early post-war years. The Chief, Taffy Bowen, was firmly in command: young, confident, cheerful and breezy, always optimistic and giving the impression that he knew exactly where he was going. He had supervised the transition of the laboratory from its wartime programme of military radar to its new peacetime policy. By the mid-1950s, the laboratory’s activities had narrowed down to two large programmes: cloud physics under Taffy’s direction, and radio astronomy under Joe Pawsey’s. Both programmes stood high in international repute.

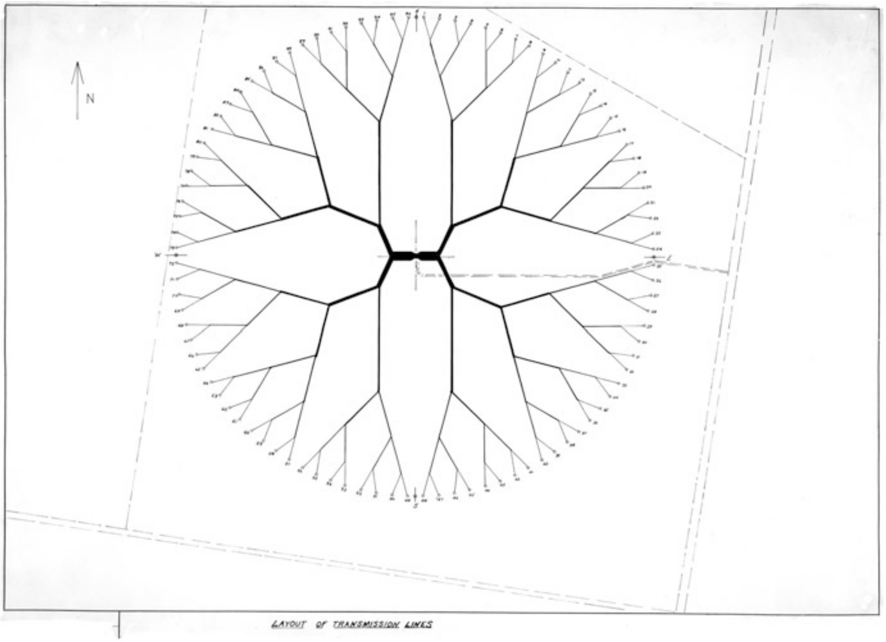


Fig. 5.29 A plan layout of the transmission lines of the radioheliograph that bring the signals from each of the 96 aerials back to the receiver via a common path length (CSIRO Radio Astronomy Historical Photographic Archives B7741-1)

When Bowen left, the Division was split into two, Radiophysics and Cloud Physics, and Paul took over as Chief of the Division of Radiophysics (see Figs. 5.36 and 5.37). While continuing his interest in the solar area, he now looked for opportunities to use the skills gained from the radio astronomy work to provide a balance of pure and applied work in the Division.

> I found myself being chief of a division that was doing nothing but pure research, and I felt very exposed. And I thought it was very important, as an insurance policy, really, to protect radio astronomy, to get involved in some applied project which was easily seen to be useful to the community, yet using the techniques of radio astronomy.

Discussions with Egon Stern from Australia's Department of Civil Aviation identified a microwave landing system as a replacement for the internationally standard instrument landing system (ILS) as a key opportunity. This was taken up with great enthusiasm by Paul. These discussions coincided with the call by the International Civil Aviation Organisation (ICAO) for member states to propose new systems. Four countries – the USA, Britain, France and Germany – had put in submissions, and Paul (with Stern's support) decided to put in an Australian submission.

Fig. 5.30 Construction of the receiver and computer building at Culgoora in 1964 (CSIRO Radio Astronomy Historical Photographic Archives B7660-5)

Paul had devised a very simple and attractive approach: the Interscan system (see Fig. 5.38). In this system, a beam is swept from left to right and then from right to left in a few milliseconds. The aircraft picks up two pips and can tell its angular position by the time spacing of these. The idea was to allow aircraft to use curved approaches, in contrast to the then-current practice of having a straight approach with aircraft queued for 10–15 miles, and to have a system that was robust against reflections and climatic environmental conditions. The implementation of this system was a major development project for the Division that drew on the extensive experience from radio astronomy.

In 1974, the American scanning beam system failed against a Doppler system in an evaluation and provided an opening for the Interscan system. After the subsequent evaluation where the simplicity and superb test results shone through (see Fig. 5.39), the Americans adopted the Interscan system. Subsequently, the Soviet

Fig. 5.31 An aerial view of Culgoora in 1964 showing the 3 km diameter ring of 96 aerials of the radioheliograph in 1964. The equipment buildings are in the *centre* of the *circle*. The trails for the transmission are visible as the cleared paths through the trees. The view is looking towards the northeast, with Yarrie Lake Road showing on the bottom right (CSIRO Radio Astronomy Historical Photographic Archives B7660-25)

Union adopted it, and in a full ICAO meeting in 1978, Interscan was selected as the international standard. At this stage, the Americans called it the "time reference scanning beam" system. The take-up of the system slowed through the 1980s and 1990s with the development of GP-based systems so that it never reached its full potential.

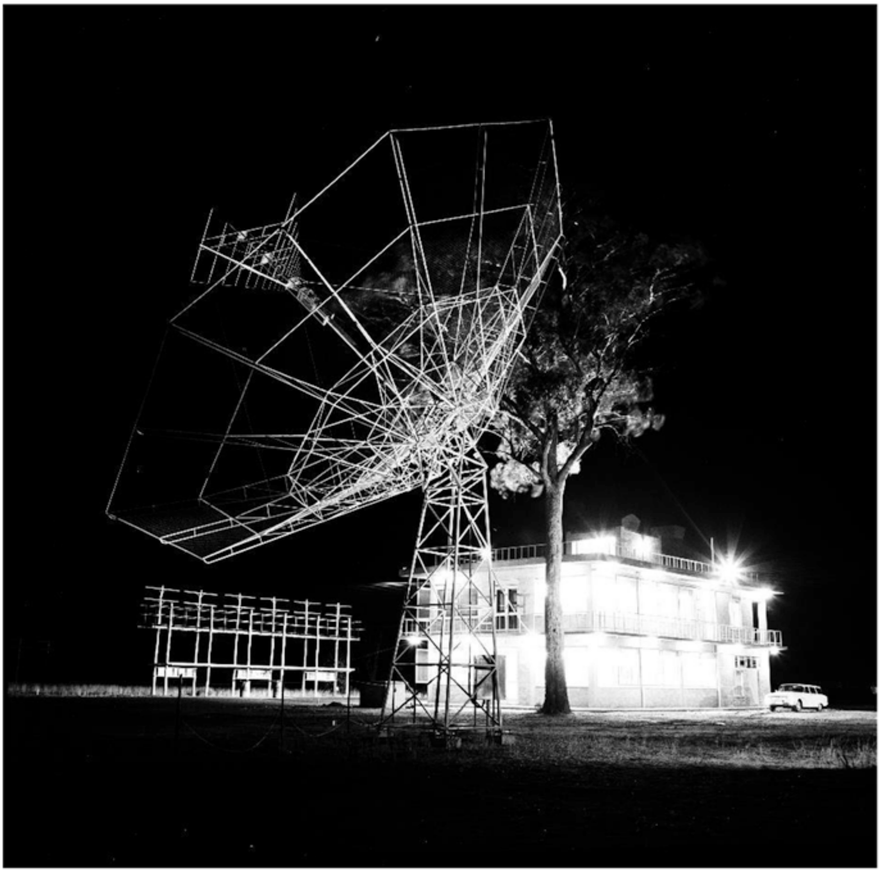


Fig. 5.32 A night-time view in 1966 of the Culgoora receiver building with the log-periodic spectrograph aerial in the foreground (CSIRO Radio Astronomy Historical Photographic Archives B8156-26)

Chairman of CSIRO

In 1976 the government appointed a three-person committee chaired by Professor Arthur Birch to carry out a comprehensive review of CSIRO (see Fig. 5.40). The committee recommended that the principal type of research performed by CSIRO should be strategic long-term, directed in support of primary, secondary and tertiary industry, or in areas of community interest such as the environment, or in relation to national obligations such as astronomy or oceanography. The committee recommended that the 37 divisions of CSIRO be grouped into five institutes, each headed by a director, and that the executive be reduced in size to three full-time members, including the chairman, and five part-time members. The government

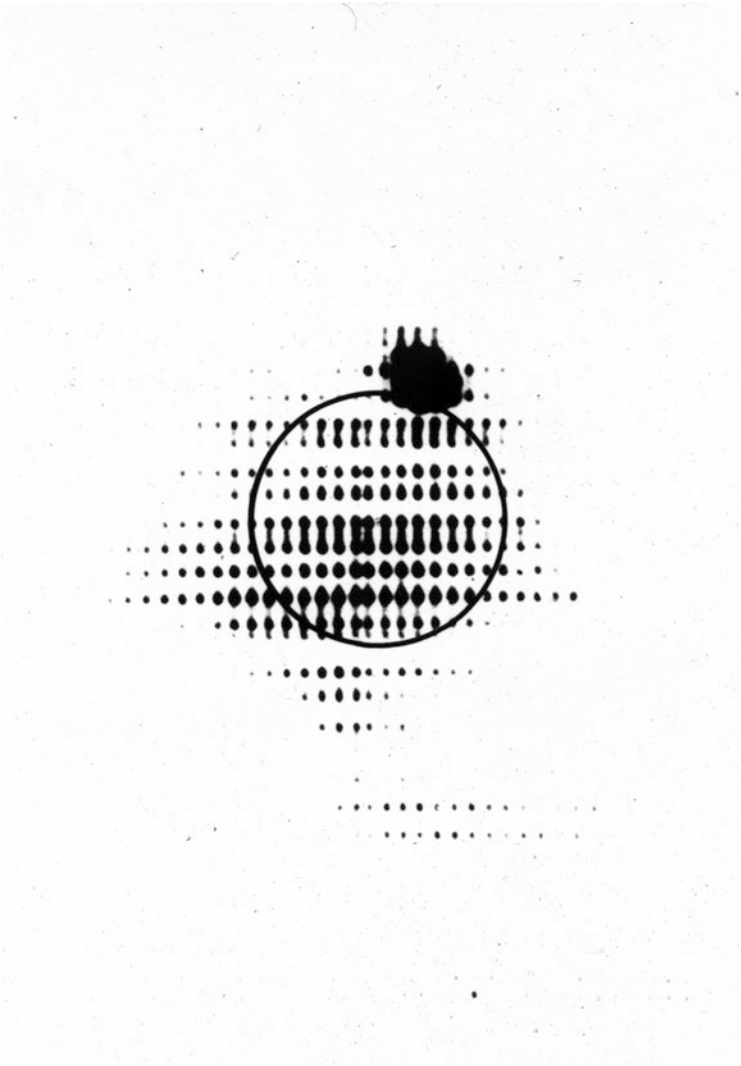
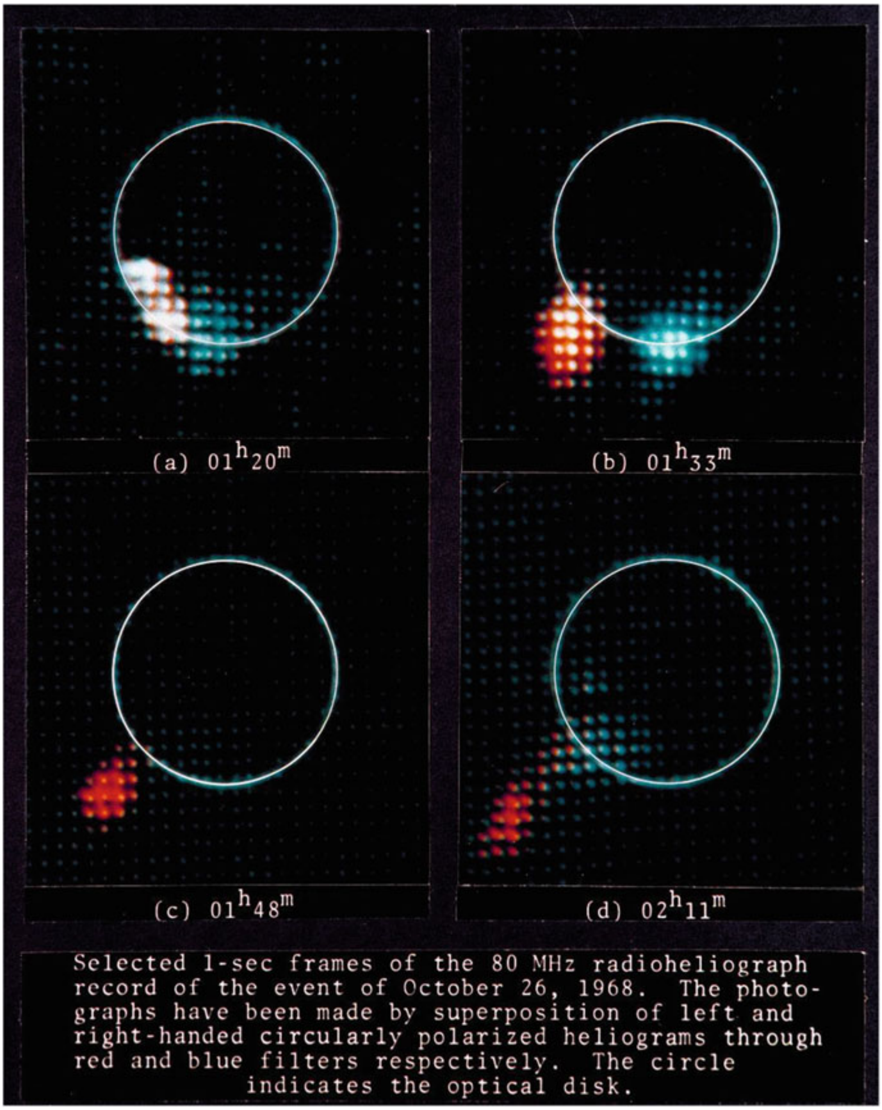


Fig. 5.33 An image from the first solar event recorded by the Culgoora radioheliograph on September 1967, just prior to the official opening of the Culgoora Observatory. The image shows the 80 MHz emission from the quiet sun with two strong bursts occurring within the corona. The *circle* on the image shows the size and position of the optical disk of the sun. The image is a 60 (E-W) × 48 (N-S) rectangular raster of points spaced 2.1 min of arc with a total field of view of 2.1° by 1.7° (CSIRO Radio Astronomy Historical Photographic Archives B8740-3)

accepted most of the recommendations of the Birch committee and sought the committee's advice on the appointment of the chairman.

Paul Wild was appointed chairman in July 1978 for a term of 7 years. He led the Organisation through the restructure. He established the institutes and appointed



Selected 1-sec frames of the 80 MHz radioheliograph record of the event of October 26, 1968. The photographs have been made by superposition of left and right-handed circularly polarized heliograms through red and blue filters respectively. The circle indicates the optical disk.

Fig. 5.34 A colour example of a solar burst recorded in a series of images by the radioheliograph (CSIRO Radio Astronomy Historical Photographic Archives N9258)

their directors. In the interviews to select the directors, Paul sought, among other things, the views of the candidates on the appropriate balance in types of research, ways to improve the interaction with the users of the research and the application of the successful research. He also established a new Division of Information Technology. He was a strong proponent for the construction of the Australian Animal Health Laboratory, a sophisticated facility for handling animal disease agents under

Fig. 5.35 A sunset view of one of the 13 m aerials of the radioheliograph (CSIRO Radio Astronomy Historical Photographic Archives N8836-8)

very secure containment conditions. Paul helped establish a laboratory and a research vessel for marine science, including fisheries and physical oceanography. The Australia Telescope, consisting of a compact array of six antennas at Narrabri that could be linked to one at Coonabarabran and the Parkes radio telescope, was built on the site of Paul's radioheliograph, and the observatory was named the "Paul Wild Observatory" (Frater, Brooks, & Whiteoak, 1992). An Australian bicentennial project, the Australia Telescope was officially opened by Prime Minister Bob Hawke in September 1988.

Two other notable outcomes from CSIRO research during Paul's chairmanship were the high-security polymer banknote developed in collaboration with the Reserve Bank of Australia and the anti-influenza drug Relenza, developed in collaboration with the Victorian College of Pharmacy.

Fig. 5.36 Paul Wild with Dick McGee watching the moon landing of Apollo 15 at Parkes in 1971 (CSIRO Radio Astronomy Historical Photographic Archives B9687-1)

Gravitational Theory

A long-standing interest of Paul's was gravitational theory. In his later years, he published a modified Newtonian theory of gravity that satisfies the demands of special relativity. The resulting theory is simpler than the general theory of relativity but still yields the Schwarzschild metric and makes equivalent predictions. Although this is acknowledged as a valid and complementary approach to the theory of general relativity, it has had limited impact. Paul's deep physical understanding of gravity theory led him to an insight that provided a link between inertial and gravitational mass and a prediction of the mass density of the universe. This would have been a significant extension of his gravity theory beyond a complementary approach, but the work was still incomplete when he died.

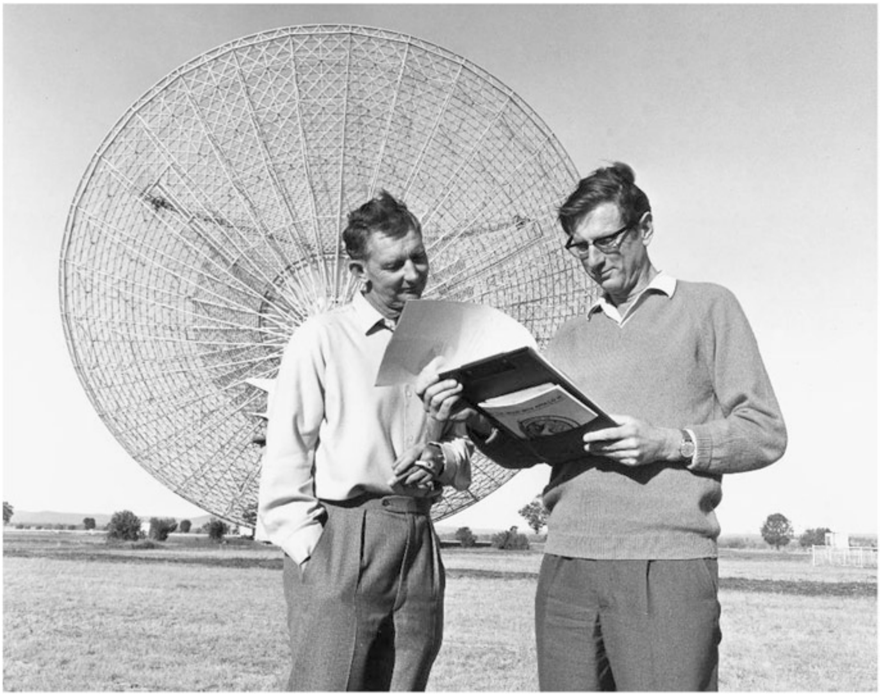


Fig. 5.37 Paul Wild and John Bolton at the Parkes Observatory in 1971 (CSIRO Radio Astronomy Historical Photographic Archives R9687-42)

Other Contributions

Paul played a number of broader roles in the astronomy and wider scientific communities. He became a member of the Anglo-Australian Telescope Board in 1973 and was there through the difficult times of deciding on the location of a Sydney headquarters and laboratory on the Radiophysics site at Marsfield. Paul was greatly relieved when Sir Harrie Massey worked with the staff and the communities to arrive at that conclusion. This provided a broader interaction base for the astronomers of the Anglo-Australian Observatory and the Radiophysics Division.

Paul served as foreign secretary of the Australian Academy of Science, 1973–1977, and was president of the International Astronomical Union's Commission on Radio Astronomy, 1967–1970.

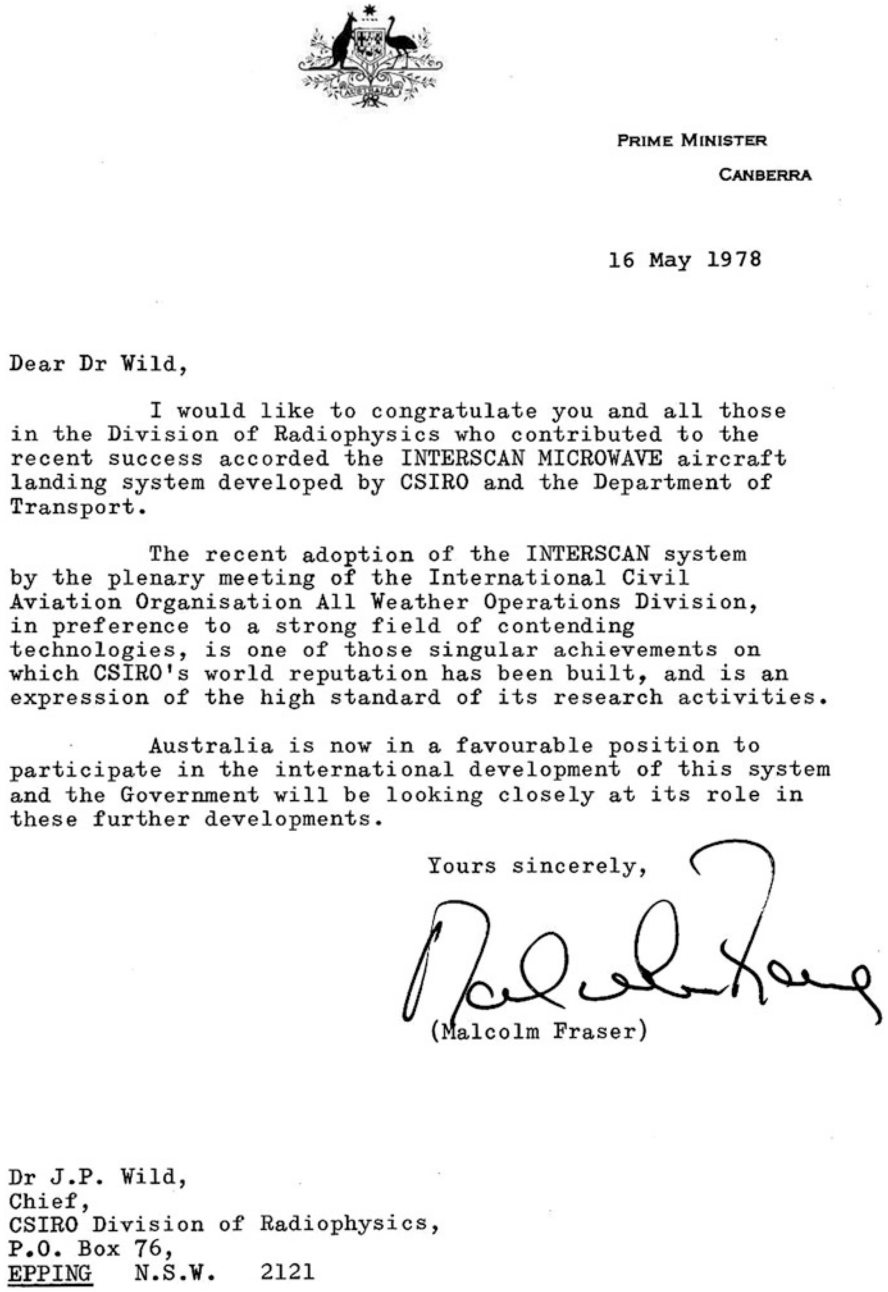
Fig. 5.38 The prototype of the Interscan landing system at Melbourne Airport in 1975 (CSIRO Radio Astronomy Historical Photographic Archives B10802-17)

Paul Wild: The Man

Throughout his life, Paul was highly respected by his superiors, his peers and those who worked for him, but he was a generally reserved, private person.

Jim Roberts, one of Paul's colleagues in the early days at Dapto, describes what it was like working with him and particularly, "the humanity of the man". Jim recalls:

> Personally, I benefited greatly from Paul's nurturing and kindness. He taught me a great deal about radio astronomy and fostered my career in many ways—I imagine he was disappointed at my failure to capitalise on some of the opportunities he offered. He treated this new boy as an equal colleague, inviting me to tennis with his friends, etc. He even taught me to drive—initially round the paddocks at Dapto and then as a learner driver of his car on our weekly trips to Dapto.



PRIME MINISTER
CANBERRA

16 May 1978

Dear Dr Wild,

I would like to congratulate you and all those in the Division of Radiophysics who contributed to the recent success accorded the INTERSCAN MICROWAVE aircraft landing system developed by CSIRO and the Department of Transport.

The recent adoption of the INTERSCAN system by the plenary meeting of the International Civil Aviation Organisation All Weather Operations Division, in preference to a strong field of contending technologies, is one of those singular achievements on which CSIRO's world reputation has been built, and is an expression of the high standard of its research activities.

Australia is now in a favourable position to participate in the international development of this system and the Government will be looking closely at its role in these further developments.

Yours sincerely,

(Malcolm Fraser)

Dr J.P. Wild,
Chief,
CSIRO Division of Radiophysics,
P.O. Box 76,
<u>EPPING</u> N.S.W. 2121

Fig. 5.39 Letter of congratulations from the Australian Prime Minister (CSIRO Radio Astronomy Historical Photographic Archives B11900)

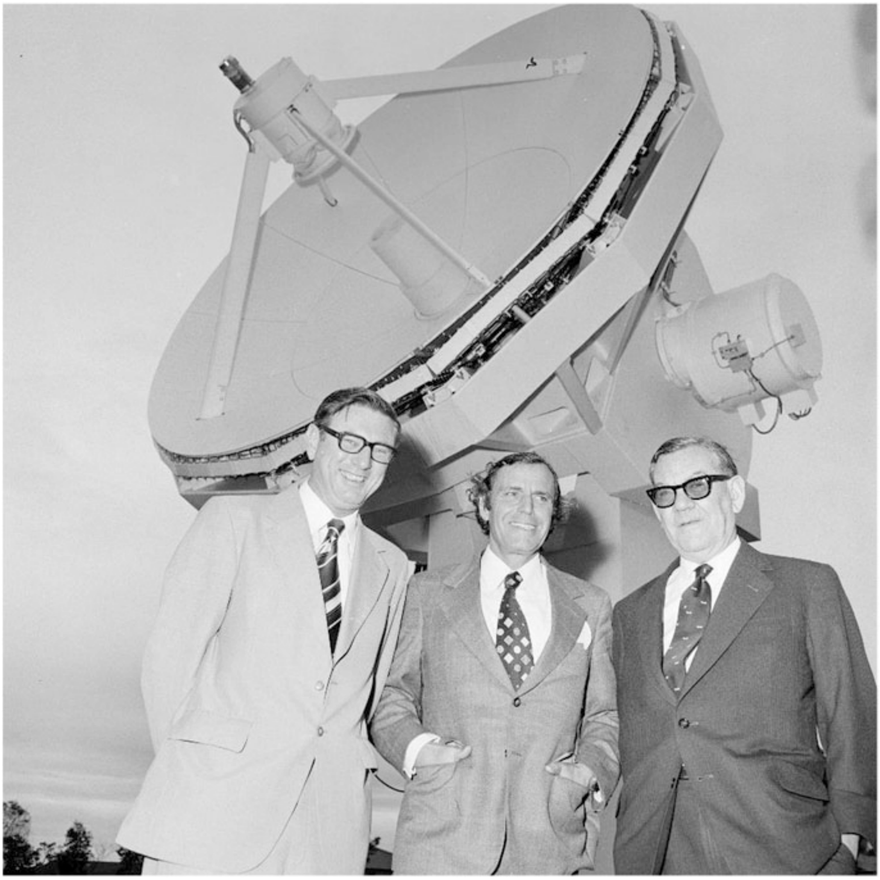


Fig. 5.40 Paul Wild (*left*), Senator the Hon. J.J. Webster, Minister of State for Science, and Sir James R. Price (1912–1999), Chairman of the CSIRO at the official opening of the 4 m radio telescope at the Radiophysics headquarters at Marsfield on 13 August 1976. This telescope was used to observe at millimetre wavelengths for the study of molecular line emission in the southern Milky Way (CSIRO Radio Astronomy Historical Photographic Archives B11354-10)

When he commenced as Chief of Radiophysics, Bob Frater recalls going to meet Paul to tell him that he thought the radioheliograph should be closed down. Bob explained his position, and, to his surprise, Paul immediately put him at ease and agreed that it was the right decision. He was supporting the person he had appointed as Chief in a very difficult decision. Paul was an enthusiastic supporter of the Australia Telescope from proposal to completion.

Ray Haynes captured the general view:

> His relaxed manner and infectious enthusiasm inspired great loyalty and devotion from his staff, and many a productive scientific discussion occurred at the hotel opposite the Laboratory or at the local rugby club on the way home at night. (Haynes, Haynes, Malin, & McGee, 1996)[5]

Summary

Paul Wild stands as one of the founding fathers of Australian radio astronomy, a towering figure in the solar arena and a great scientific leader on the broader scene. He spent his entire professional career in CSIRO, despite some very attractive offers from elsewhere. The "big-picture" people in science, the "systems thinkers" who can see their way through the complexity to set the path, are the ones who take the world forward. In this arena, Paul was in the absolute top drawer. He clearly had an exceptional intellect, wide knowledge and a continuing and unstoppable interest in "the new". During his career he published around 100 research papers.

Paul gained many honours including the Hale Prize in 1980. He was a Fellow of the Australian Academy of Science and of the Australian Academy of Technological Sciences and Engineering, a Fellow of the Royal Society of London and a Foreign Member of the American Philosophical Society and of the American Academy of Arts and Sciences. He was made a Commander of the Order of the British Empire (CBE) in 1978 and a Companion of the Order of Australia (AC) in 1986.

Paul's wife Elaine died in 1991. He subsequently married Margaret Haddock and spent his last years between Margaret's home in Ann Arbor, Michigan, in the USA, and his home in Canberra. He died in 2008. Paul is survived by his daughter Penny, his sons Peter and Tim and Tim's children Arnold and Victor.

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[5] Paul Wild was the subject of a long-running barroom tale – see Appendix B.

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Chapter 6
Ron Bracewell: Mathematics and Imaging

Ronald Newbold Bracewell (Fig. 6.1) was born in Sydney, Australia, on 22 July 1921, one of two sons of Cecil and Valerie Bracewell.

Though his own education was poor, Cecil had grown up in circumstances where education was valued. He had a complete set of the works of Charles Dickens, several volumes of which Ron read as a child. He had a *Concise Oxford Dictionary* that he referred to frequently and used for discussion of questions of grammar. He, nor Valerie, had any science background but as Ron said:

> There were lots of uncles and aunts, some of them practical people who did things with their hands. One of my uncles was a cabinet maker and two others grew grapes at Glenfield, and they could do things with their hands, savvy people. When I went to Glenfield, they'd always be reading the latest report from the Department of Agriculture about how to improve the soil and things like that but nothing of a serious scientific kind, however. (Bhathal, 2000)

Childhood

When he was quite young, Ron had a Meccano set:

> I made all the usual things with that, and my friends had them, too, so we would lend parts to one another. In fact, that would be quite an influential consideration, I believe, learning to use nuts and bolts and configure things in your head. I think that's quite a useful early experience. I know when I was about six I got a small aeroplane with a wind-up propeller, a clockwork propeller, and you hung it from the ceiling on a piece of string and it flew in circles. Later on I made model aeroplanes with rubber bands inside them, and I got interested in kites for a short time, too. (Bhathal, 2000)

Ron's father had been confirmed in the Anglican church but didn't go to church, and his mother didn't go to church unless there was a wedding. Ron, however, was sent off to Sunday school:

R.H. Frater et al., *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, Astronomers' Universe, DOI 10.1007/978-3-319-65599-4_6

Fig. 6.1 Ronald Newbold Bracewell (Courtesy of the Goss Collection)

> When I was seven or eight I can remember receiving small coloured texts at Sunday school. (These were found by Mark Bracewell, Bob Lash and Miller Goss in July 2009 in the Bracewell family archive.) They would have a colour picture of the Good Shepherd and two or three lines taken from the New Testament. It's not something you like to do every Sunday, but I was certainly sent along, though I don't quite understand why that was.
>
> At age 14, I was confirmed. The most attractive aspect of that was all the 14-year-old girls were being instructed at the same time. St Jude's church—that was in Randwick—had the good idea of putting on dances on Thursday nights. That was truly exciting, a lot to say for religion in that respect. (Bhathal, 2000)

When asked later, whether, as a scientist, he believed there was a God, Ron replied, "As a scientist, I don't know".

Ron was given a *Pear's Cyclopaedia,* which he read from beginning to end. He read adventure stories, and when he was about 10 or 11 or 12, he started reading science fiction: things that H.G. Wells wrote and some of the better-known science fiction. He absorbed all of that.

In 1932 the Department of Education introduced the IQ test. As a result, Ron found himself in the very first of the special opportunity classes in Woollahra, in the eastern suburbs of Sydney. He went from there to the Sydney Boys' High School from 1933 to 1937. In addition to science and mathematics, he was interested in languages and passed oral exams in French and German. In 1937 he was awarded the Alliance Française Prize and came in third in the state in French.

He remembers:

> In elementary school, I found nature study interesting. When I went to school in Lakemba, they would take us out and show us seeds and show us caterpillars. In fact, they made us collect caterpillars and feed them and watch them hatch out into various sorts of moths and butterflies. I thought that was pretty good, and it probably influenced me quite a bit. . .In high school I found that chemistry was pretty good, and it wasn't long before I was doing my best to make bad stinks and explosions. . .I didn't damage myself fortunately. At the

> same time, I thought geometry was really interesting. We must have had some good teachers. I liked geometry, and I liked algebra—I thought that was pretty good.
>
> At the same time we were learning Latin and French, and I think that Latin is just like geometry, it causes you to think. It's so unbelievable that they would have grammar the way they did, and you have to obey rules. It's very much like mathematics, and I think it has the same influence on you as geometry does…
>
> All through my 5 years at Sydney High School I was interested in chemistry. Then towards the end when we started doing experiments in physics, I thought they were very interesting, too, like plotting rays of light through blocks of glass using pins and pencil and paper. That got my attention.
>
> I remember the teacher in chemistry coming out one day with half a beaker full of hydrochloric acid and half a beaker full of sodium hydroxide, pouring them together and testing them with some litmus paper and then taking a mouthful of this stuff and spitting it down the sink. Looking back, I see that's extremely dangerous because if you got that slightly wrong, it would be bad. But it was impressive to know that by deduction and thinking you could convert two very dangerous things into something that you could put in your mouth without danger. (Bhathal, 2000)

He recalls his pathway to engineering:

> I was so interested in chemistry my father thought he would get the advice of an industrial psychologist, Haigwood Masters, who had an office in the T&G building. So I had two sessions with him, and his recommendation was that I should learn Japanese and go into the wool-selling business, or, since I was then doing quite well at French, I should become a court interpreter, or go into industrial chemistry. So my father then consulted a physics teacher at Sydney Grammar School, and he said that when I went to Sydney University I should not go into the faculty of science, which was my intention, "Because", he said, "if you do that, you will study physics, chemistry, mathematics and something else like geology or botany", which he gave me to understand didn't really count. "But", he said, "if you go into first-year engineering you will be studying physics, chemistry, mathematics and four other subjects, so at the end of first year you would have more options open".
>
> So this appealed to me, and I did that, and at the end of the first year I had completely lost my interest in chemistry because I hadn't learnt anything that I wasn't already vaguely familiar with, whereas I was learning all this really good mathematics and physics which caught my attention, so I stayed with that. (Bhathal, 2000)

Ron went on to Sydney University and, in 1941, graduated with a BSc degree in Physics and Mathematics. In 1943 he earned an Honours degree in Electrical Engineering.

On graduation, he worked at the Radiophysics Laboratory of CSIRO with Joe Pawsey on development of radar and radio communications (see Fig. 6.2). In 1946, after the war, Ron went to Sidney Sussex College at Cambridge (England) as J. A. Ratcliffe's graduate student. His research topic was the study of the ionosphere using propagation measurements at 16 kHz, for which he obtained his PhD in 1949 (see Fig. 6.3). The ionospheric work resulted in the discovery that the D-layer ionisation consists of two components, for which he was awarded the Duddell Premium of the Institute of Electrical Engineers in 1952.

The effect of solar activity on the ionosphere was one of the factors that led to Bracewell's lifelong interest in the sun (i.e. Bracewell & Straker, 1949). He

Fig. 6.2 Ron Bracewell (*centre*, standing) hiking with the CSIRO Ski Club in the 1950s. Arthur Watkinson is on the far *right* and Warren Peyton is in the white hat (Courtesy of the Goss Collection)

invented the word "ionomers" to distinguish those interested in the ionosphere from "radio astronomers". His interest in the theory and applications of Fourier transforms,[1] which was initiated by mathematics courses at Sydney University, was further stimulated by Ratcliffe, who was a recognised authority on the subject.

Introduction to Radio Astronomy

In 1949 Bracewell returned to Australia and again took up a position at CSIRO. Initially he continued his work on the ionosphere, but soon became involved in radio astronomy. He helped on the organising committee for the 1952 URSI conference held in Sydney which showcased the developments by Radiophysics to the international community. One of his contributions was to design the lapel pin given to each delegate (see Fig. 6.4).

Bracewell shared an office with radio astronomers W.N. "Chris" Christiansen (1913–2007) and Harry Minnett (1917–2003), who were working on solar radio observations (see Orchiston, Slee, & Burman, 2006). Christiansen had built grating

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[1] The mathematical process used in radio astronomy to produce images using aperture synthesis techniques.

Fig. 6.3 Ron Bracewell in a punt boat at Cambridge in the late 1940s while a graduate student with J.A. Ratcliffe (Courtesy of the Goss Collection)

arrays of parabolic antennas, aligned in north-south and east-west directions, along the edges of a reservoir at Potts Hill near Sydney (see Wendt, Orchiston, & Slee, 2008). These produced fan-beam scans of the sun over a range of angles each day. From these it was possible to derive radio brightness contours of the sun in two dimensions (see Christiansen & Warburton, 1955a, b). Bracewell was interested in this analysis, which involved Fourier transforms. He was also intrigued by the possibility of using two grating arrays to produce a matrix of pencil beams, using the cross configuration developed by Bernie Mills (1920–2011) for linear arrays (see Mills & Little, 1953) (see Fig. 6.5).

Fig. 6.4 The lapel pin designed by Bracewell for the 1952 URSI meeting held in Sydney and given by Bracewell to Goss in 2007 (Courtesy of the Goss Collection)

Fig. 6.5 (L-R) Bracewell, Bernie Mills and Kevin Westfold in 1954 examining part of the Mills cross array at Fleurs field station (Courtesy of the Goss Collection)

During this time, Joe Pawsey, the leader of the radio astronomy group, invited Ron to be co-author of the book *Radio Astronomy* (Pawsey & Bracewell, 1955), and Ron later surmised that this was partly a device to get him more involved in the field of radio astronomy. Pawsey also asked him to produce a pictorial dictionary of Fourier transforms, which later led to Bracewell's most important book, *The Fourier Transform and its Applications* (Bracewell, 1965). During the academic year 1954–1955, he was invited by Otto Struve (1897–1963) to give a series of lectures on radio astronomy at the University of California, Berkeley. He also lectured at Stanford University, which led to his joining the Electrical Engineering Department at Stanford in December 1955. An interesting autobiographical account of the period from his first interest in radio astronomy through the early years at Stanford can be found in his paper, "Early work on imaging theory in radio astronomy", published in Sullivan's *The Early Years of Radio Astronomy* (1984), while his recollections of the Stanford years can be found in Bracewell (2005).

Important Early Papers and a Book

During the period 1949–1965, from his first interest in radio astronomy through his early years at Stanford, Bracewell produced a number of publications on interferometer theory, imaging with interferometers and arrays, and data analysis that established his expertise in this area. Examples of notable publications are discussed below:

- *Aerial smoothing in radio astronomy* (Bracewell & Roberts, 1954). This paper was particularly important in the early years of radio astronomy, when the relation between the true profile of a source and the profile obtained by scanning with an antenna was not well understood. Bracewell and James A. (Jim) Roberts (1927–) explained the scanning as a convolution of the brightness function and the point-source response of the antenna.[2] This understanding provided essential insights into the observing process. The later part of the paper is concerned with reducing the effect of aerial smoothing by analytically adjusting the antenna response so that all of the Fourier spatial components to which it responds are given equal weight. Bracewell referred to this process as restoration and the resulting profile as the *principal response*.[3] The angular resolution is usually

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[2] The convolution theorem of Fourier transforms shows that the Fourier components of the source profile are filtered by the Fourier spectrum of the antenna response. The concept of invisible distributions (i.e. Fourier components not detectable with a given aperture distribution) was introduced in this paper.

[3] A function derived from two given functions by integration that expresses how the shape of one is modified by the other. In other words – take a series of data and apply another known function to this that SMOOTHS the data.

improved by the restoration process, but the sharp cut-off in angular frequency at the maximum to which the antenna system responds can result in prominent side lobes, limiting the dynamic range.[4]

- *Strip integration in radio astronomy* (Bracewell, 1956). This paper considered the construction of two-dimensional images from one-dimensional scans of a source with a range of position angles as was required, for example, to obtain a solar image from Christiansen's early grating array observations. The Fourier transform relationships involved are succinctly illustrated in a diagram (Fig. 6.5 in his paper) which Bracewell later refers to in his chapter in Sullivan's (1984) book as the "projection-slice theorem". He used the term reconstruction to describe this method of production of two-dimensional images, a technique which was later adapted to tomography. Further development can be found in "Inversion of fan beam scans in radio astronomy" (Bracewell & Riddle, 1967).
- *Radio interferometry of discrete sources* (Bracewell, 1958). This paper provided a precise development of the interferometer response and the Fourier transform relationship between the fringe visibility and the brightness distribution. The paper also unified material discussed in earlier publications by various authors. Bracewell introduced the use of direction cosines for the angular coordinates on the sky, thereby avoiding the small-angle approximation used in most of the earlier discussions of interferometry. This paper also utilised the sampling theorem of Fourier transforms to determine the most efficient choice of the spacings of antennas in interferometry.
- *Tolerance theory of large antennas*. Bracewell (1961) published a theoretical discussion of the impact of surface errors on the performance of large single dishes. He considered "the effects of systematic and random errors on the radiation pattern of antennas represented by a field distribution over an aperture. . .Practical steps are considered for unifying testing, adjusting and design" in order that the most optimal antenna could be manufactured.
- *The Fourier Transform and its Applications* (Bracewell, 1965). The end of this period saw the publication of Bracewell's most important book, *The Fourier Transform and its Applications*. This book cemented the early "physical versus mathematical" learnings from Pawsey and the period with Ratcliffe, in a book that became the Fourier transform "bible" for many in the radio astronomy scene. The book has been updated in many editions (Polish translation in 1968, 2nd Edition in 1980, revised 2nd Edition in 1986, 3rd Edition in 2000 and a Chinese translation in 2005), and through it, Bracewell established a level of recognition for his elucidation of the convolution theorem and its importance in the interpretation of observations. He developed a reputation for his demanding exactitude from those who worked in his space.

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[4] The dynamic range is the ratio between the maximum and minimum quantity that a system can reliably measure.

Stanford and the Heliopolis Observatory

In 1955, Ron and his wife Helen, whom he had married 2 years earlier, moved to California where Ron became the Lewis M. Terman Professor of Electrical Engineering. He established a Radio Astronomy Institute and developed an observatory, which he named Heliopolis, on the outskirts of the Stanford lands.

The first instrument developed at Heliopolis was a solar cross, i.e. a crossed-grating array for solar observations, as he had considered earlier while at CSIRO. This array was made to Bracewell's design and consisted of 32 parabolic antennas arranged in two linear arrays and operated at 9.1 cm wavelength. Bracewell named the instrument the Stanford Microwave Spectroheliograph. It is described by Bracewell and Swarup (1961). Phase adjustment of the cross led to the invention of the round-trip phase measurement technique[5] by Bracewell's graduate student Govind Swarup (1929–; see Figs. 6.6 and 6.7),[6] which is described by Swarup and Yang (1961). An adaptation of this round-trip technique has subsequently been used in almost all large radio astronomy arrays.

The heliograph was used to make daily images of the sun, with an angular resolution of 3.2 arcmin, from June 1962 to August 1973 (see Figs. 6.8 and 6.9). These were published monthly, and the observations also resulted in a number of papers on radio emission from the solar corona. Two additional antennas (see Fig. 6.10) were added to extend the east-west arm of the cross to form a compound interferometer. This produced fan beams of width 52 arcsec, and east-west scans of several strong radio sources were obtained with this angular resolution (Swarup, Thompson, & Bracewell, 1963; Thompson & Krishnan, 1965).

The east-west arm of the cross array was also used to study the radio source Centaurus A, a radio galaxy that was strong, optically identified and of sufficient angular width that the beam of the arm could reveal interesting structural detail.[7] The two components of the central part of the source (separated by 4.8 arcmin) were described by Little, Cudaback and Bracewell (1964).

There also were two 30 ft. diameter equatorially mounted parabolic antennas, and during the 1960s, these were used as a two-element interferometer at 9.8 cm

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[5] The round-trip phase measurement involves transmitting a signal from a central point in the array to each aerial, then comparing the phases of the transmitted and reflected signals. Based on this comparison, a small change to the length of the cable is applied to correct for changes in cable length due to temperature, etc.

[6] For details of Swarup's career, see Swarup, G. 2006. Potts Hill to Kalyan: the saga of beginning radio astronomy in India. *Journal of Astronomical History and Heritage,* 9, 21–33. and Goss, W. M. Origins of radio astronomy at the Tata Institute of fundamental research and the role of J. L. Pawsey. *In:* Chengalur, J. N. & Gupta, Y., eds. The Metrewavelength Sky, 2017. Astronomical Society of India, 409.

[7] The maximum elevation of Centaurus A was too low for useful resolution with the north-south arm. For observations of Centaurus A, a parametric amplifier developed by A.G. Little (1961) was used to improve the sensitivity. Alec Little (1925–1985) obtained an MSc degree from Stanford for his amplifier work.

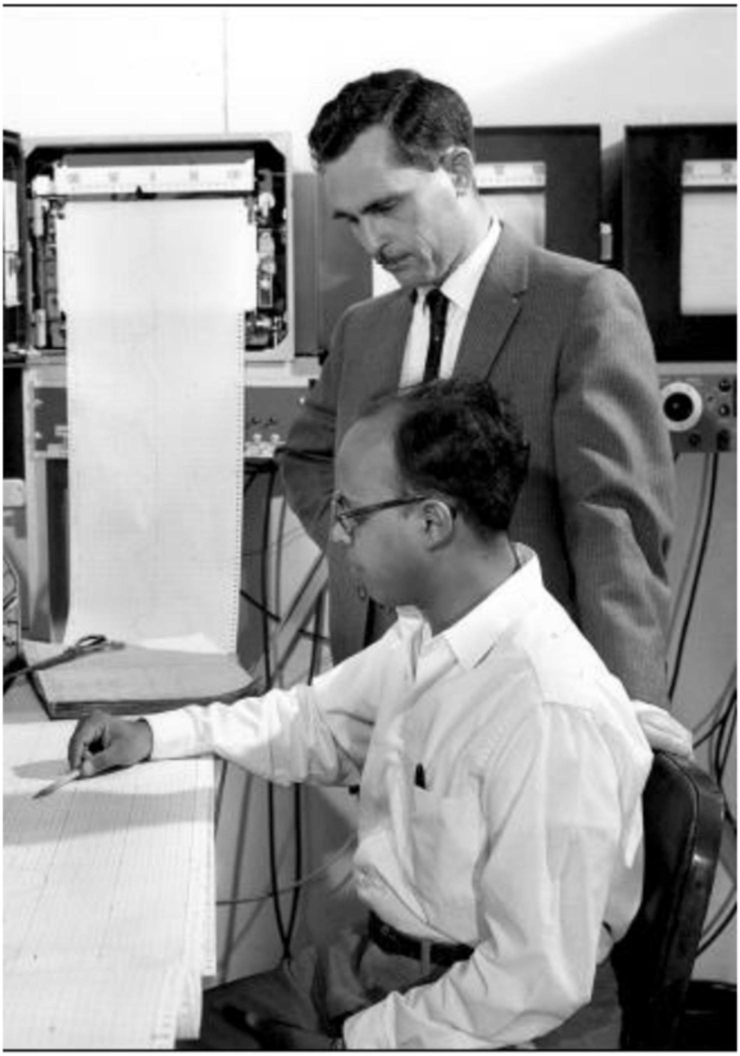

Fig. 6.6 Ron Bracewell with his PhD student Govind Swarup, who was later awarded a fellowship of the Royal Society of London for his work in radio astronomy in India. This photograph was taken about 1960 and shows them examining records of solar scans taken in the early phase of the programme with the Stanford Microwave Spectroheliograph (courtesy: Stanford University News Service)

(~3.1 GHz) (see Fig. 6.10). They could be moved among several foundations to vary the length and direction of the baseline. The interferometer provided material for several PhD theses; however the sensitivity was not sufficient for observation of more than a few of the strongest Galactic and extragalactic sources. Bracewell considered building an instrument with a much larger collecting area, using several

Fig. 6.7 (L-R) Bracewell and Govind Swarup watching Joe Pawsey carve his name into a concrete pier East-1 of the Stanford Microwave Radioheliograph in 1958 (Courtesy of the Goss Collection)

long cylindrical reflectors. He envisaged an instrument that would grow with time by the addition of more elements as funding allowed (Bracewell, Swarup, & Seeger, 1962b). However, funds for a large instrument proved to be unavailable.

At about this time, the development of earth-rotation synthesis by Martin Ryle (1918–1984) showed the advantage of fully steerable antennas. Thus, Bracewell concluded that the most economical way to obtain sensitivity would be to build an array of tracking antennas which could be designed and constructed under his direction. This resulted in five 18.3 m (60 ft) diameter antennas, which were made to Bracewell's design and constructed on-site at Heliopolis (see Figs. 6.11 and 6.12). The antennas were configured as an east-west, minimum-redundancy, linear array devised by Bracewell (1966), in which all spacings up to nine times the unit spacing are included. The operating frequency was 10.7 GHz, allowing synthesis of a beam of width 18.8 arcsec. A well-illustrated description of the construction project is given in Bracewell, Colvin, Price and Thompson (1971) and full details of the array in Bracewell et al. (1973).

Observations with the array provided data for a number of papers and theses by Bracewell's students, including further work on Centaurus A (Price & Stull, 1973). This array was in operation from 1972 until the closing of the Heliopolis observatory in 1979.

Fig. 6.8 The crossed-grating array named the Stanford Microwave Spectroheliograph. The array operated at a wavelength of 9.1 cm and was used to produce daily two-dimensional maps of the sun with a resolution of 3.2 min of arc from June 1962 until August 1973. The observatory was named "Heliopolis" by Bracewell (Courtesy of the Goss Collection)

The discovery in 1964 of the cosmic background radiation (CMB) by Arno Penzias (1933–) and Robert Wilson (1936–) (see Penzias & Wilson, 1965) provided a radio astronomical feature that could be investigated without the use of large antennas. While measurements of the CMB made in the early years after the discovery indicated a uniform brightness temperature, Bracewell realised that the motion of the earth with respect to the CMB would cause an observable variation. He and his graduate student E.K. Conklin were able to calculate this variation (Bracewell & Conklin, 1968). From observations at Heliopolis, only upper limits on the variation could be obtained. To reduce atmospheric absorption, the project was moved to a high elevation site in the White Mountains of California (White Mountain at elevation 4344 m), using two small horn antennas at a frequency of 8 GHz. Conklin (1969) was then able to publish a determination of the velocity of the earth from measurements of variation of the observed CMB temperature at the mK level. This experiment was the first detection of the effect, a notable achievement considering that it was made with a simple system using two small horn antennas with an uncooled receiver.

In April 1962, during a trip to Australia, Bracewell had the opportunity to observe Centaurus A with the Parkes radio telescope at 10 cm. He was able to resolve the two components in the central part by driving the telescope in both azimuth and elevation simultaneously, so as to scan in the direction of the component separation. He also was able to rotate the feed and discover the linear polarisation. However, there appeared to be some question of whether the

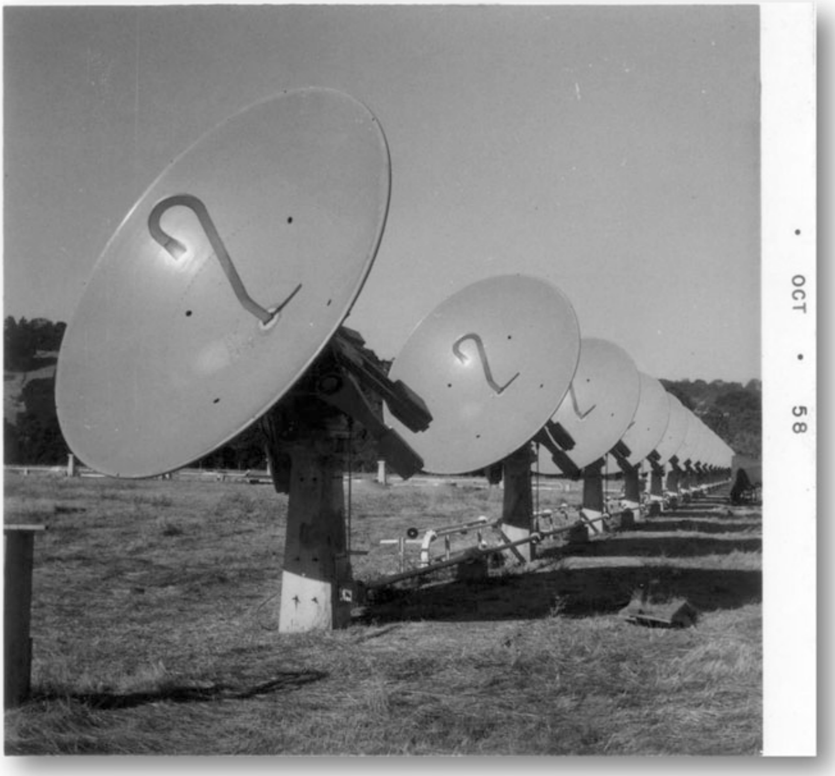

Fig. 6.9 A close-up image of the 32 element crossed solar grating array at Heliopolis in October 1958 (Courtesy of the Goss Collection)

observation was made during an officially granted observing period. Bracewell's letter to *Nature* (Bracewell, Cooper, & Cousins, 1962a) was not published until 29 September 1962. Meanwhile, other observations from Parkes, made shortly after Bracewell's, also reporting polarisation of Centaurus A, appeared in print 2 weeks before Bracewell's paper. More detailed accounts of these circumstances can be found in Bracewell (2002) and Haynes, Haynes, Malin and McGee (1996). In 2014, Goss and Ekers located an archive in the home of the late Sally Atkinson (Bowen's personal assistant from the 1940s until his retirement in 1971, later archivist of the Division of Radiophysics). In her archive they found a large file that provides definitive evidence that Bowen (Chief of the Division of Radiophysics at the time) had persuaded the editors of *Nature* to delay the publication of the Bracewell, Cooper and Cousins letter to insure that the results of the other observations carried out after the initial Bracewell observations were published first.

In the late 1960s, Bracewell's work on reconstruction of images from one-dimensional scans became recognised as having an important application in medical imaging by X-ray tomography. As mentioned above, the theory of

Fig. 6.10 One of the two 9.1 m (30 ft) equatorially mounted aerials used as an interferometer with the spectroheliograph array operating at 3.1 GHz. These aerials could be moved between several different foundations to vary the length and direction of the interferometer baselines (Courtesy of the Goss Collection)

reconstruction of a two-dimensional image from one-dimensional scans had been explained by Bracewell (1956). The implementation was further advanced in the paper with graduate student A.C. Riddle (1941–2005) on "Inversion of fan-beam scans in radio astronomy" (Bracewell & Riddle, 1967). In this later paper, the procedure was simplified by the avoidance of the need to compute Fourier transforms. Bracewell wrote two additional papers specifically on tomography, one with

Fig. 6.11 The E-W-oriented five-element 18.3 m (60 ft) dish array at Heliopolis with the crossed-grating array in the background. This array operated at 10.7 GHz and produced a synthesis beam of 18.8 s of arc resolution. It was in use from 1972 to 1979 (Courtesy of the Goss Collection)

Fig. 6.12 L-R K.M. Price, Ron Bracewell and W.S. Scott with one of the 18.3 m dishes in the background (Courtesy of the Goss Collection)

graduate student J. Verley (Verley & Bracewell, 1979). He also devoted a chapter on tomography in his book *Two-Dimensional Imaging* (Bracewell, 1995). For his contribution to tomography, Bracewell was awarded associate membership of the Institute of Medicine of the US National Academy of Sciences in 1962.

Bracewell as a Teacher and Mentor

Ron always presented his lectures with an infectious enthusiasm (see Fig. 6.13). He was a challenging taskmaster for his graduate students. He had a good eye for, and an appreciation of, capable people and delighted in being able to stretch their

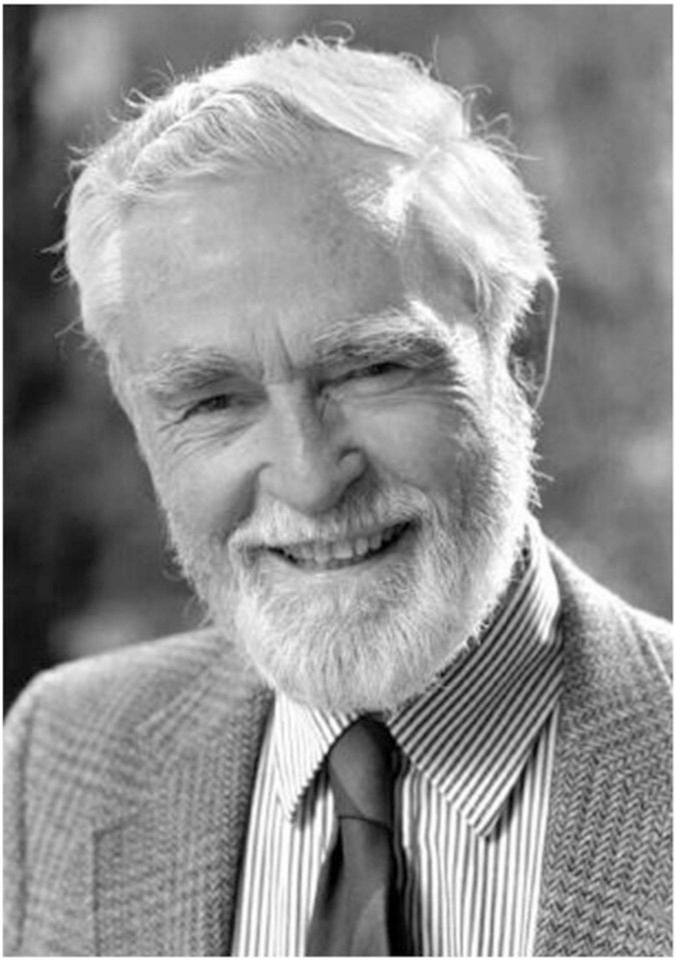

Fig. 6.13 Ron Bracewell in 1997 (photograph by Linda A. Cicero/Stanford News Service, 1997)

Fig. 6.14 Ron Bracewell at Stanford in 2007, he died not long after (Courtesy of the Goss Collection)

capabilities. He was a great mentor and always demanded clear and detailed thinking when approaching any problem. He insisted upon precise definitions and disliked making changes in them.

When examining students, Ron liked to try to judge their ingenuity and power of observation as an indication of aptitude for experimental research. During annual interviews with prospective PhD students in the Department of Electrical Engineering, he often tested their reaction to unusual things that they had not seen before. In 1 year, he asked the students to examine a sample piece of the circular waveguide used for signal transmission in the Very Large Array in New Mexico, without telling them what it was. A careful visual examination of this would show that the surface impedance of the inner wall was very low in the circumferential direction but much higher in the longitudinal direction, which could provide a clue as to its use.

Bracewell retired from teaching in 1991 (see Fig. 6.14) but continued to work in his areas of interest until his death in 2007. His list of publications from these later years contains 22 papers and 12 book reviews.

In 1994, he was awarded the Heinrich Hertz Medal of the IEEE for pioneering work in antenna aperture synthesis and image reconstruction as applied to radio astronomy and to computer-assisted tomography. In 1998, he was named Officer of the Order of Australia for his service to science in the fields of radio astronomy and image reconstruction.

Breadth of Expertise and Interest

Bracewell's mathematical expertise is evident from much of his work, especially his books on the Fourier and Hartley transforms. He also had an excellent understanding of physics, as is evident in publications such as "Rotation of artificial earth satellites" (Bracewell & Garriott, 1958) and "An observer moving in the 3° K radiation field" (Bracewell & Conklin, 1968). In Mihovilovic and Bracewell (1991), he and his student introduced the concept of chirplets as a representation for ionospheric whistler signals and similar data in a time-frequency domain. An example of his understanding of fundamental theory in engineering is the paper "Impulses concealed by singularities: transmission-line theory" (Bracewell, 1998). The remarkably wide range of Bracewell's scientific interests can be seen clearly in the diversity of the subjects of his publications and lectures.

Throughout his career, he had a long-term interest in the possibility of the existence of extraterrestrial intelligence and the practicality of extraterrestrial communication. This resulted in 19 papers and the book *The Galactic Club* (Bracewell, 1974).

An example of his interest in the history of science and engineering can be seen in the paper "Planetary influences on electrical engineering" (Bracewell, 1992). He designed sundials, one of which was installed at the Terman building on the Stanford campus and later moved to the south side of Huang Engineering Centre (see Fig. 6.15). In Chap. 1 we discuss the sundial that was built to honour Bracewell's contributions to radio astronomy.

Ron had a lifelong interest in trees, particularly those native to Australia, and in California he identified more than 70 species of the introduced eucalyptus. He wrote two books on trees of the Stanford area and had some fine examples of banksias growing in the garden of his house at Stanford.

Further Information

Some of Bracewell's own descriptions of his work can be found in his chapter in Sullivan (1984), Bracewell (2005) and the text of a recorded interview by Bhathal (2000). Bracewell's scientific papers are archived at the National Radio Astronomy Observatory, Charlottesville, VA. A complete list of his publications can be found

Fig. 6.15 Ron Bracewell in 1980 standing on one of the dilapidated piers of the Stanford Microwave Spectroheliograph and doing his best impersonation of a sundial gnomon. The signatures of visiting radio astronomers are visible on the pier which is now preserved as part of the Bracewell Radio Sundial (see Chap. 1, Courtesy of the Goss Collection)

at http://www.nrao.edu/archives/Bracewell/bracewell_top.shtml. This list includes 10 books, 218 published papers in the literature, 33 book reviews and 34 internal reports.

He was recently honoured for his scientific contributions when CSIRO named a supercomputer cluster after him (see Appendix C).

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Chapter 7
Influences of the *Four Pillars* Beyond Radio Astronomy

The influence of the *Four Pillars* has been far reaching, not only within the context of radio astronomy, but more broadly covering areas as diverse as medical imaging and the development of Wi-Fi. This influence came directly from their invention of new instruments and techniques, and more importantly from the research environments they created, their mentoring of students and their international collaborations.

Radio Telescopes

Christiansen's invention of the original grating array radio telescope[1] had an immediate influence on many overseas groups involved in solar research. Groups in France (see Fig. 7.1), Japan and India constructed their own versions of the grating arrays. Likewise, his crossed-grating array design was also quickly adopted, a notable example of which was built by Bracewell at Stanford University (Bracewell & Swarup, 1961).

In 1960, Christiansen spent 15 months at Leiden University in the Netherlands at the invitation of Professor Jan Oort to lead an international design team for the 400 MHz "Benelux Cross" Project. Here he worked with the Swedish astronomer Jan Högbom, whose PhD thesis included chapters on aperture synthesis theory and earth-rotational synthesis. The Benelux Cross Project was eventually abandoned after the Belgians pulled out of the joint venture. However, the Dutch persisted, eventually dropping the cross design option and proceeding with a linear array using earth-rotational aperture synthesis more along the

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[1] The concept of the grating array was also independently developed in Japan, although an instrument was not constructed until after Christiansen's first array was built (see Sullivan, 1984: 337).

R.H. Frater et al., *Four Pillars of Radio Astronomy: Mills, Christiansen, Wild, Bracewell*, Astronomers' Universe, DOI 10.1007/978-3-319-65599-4_7

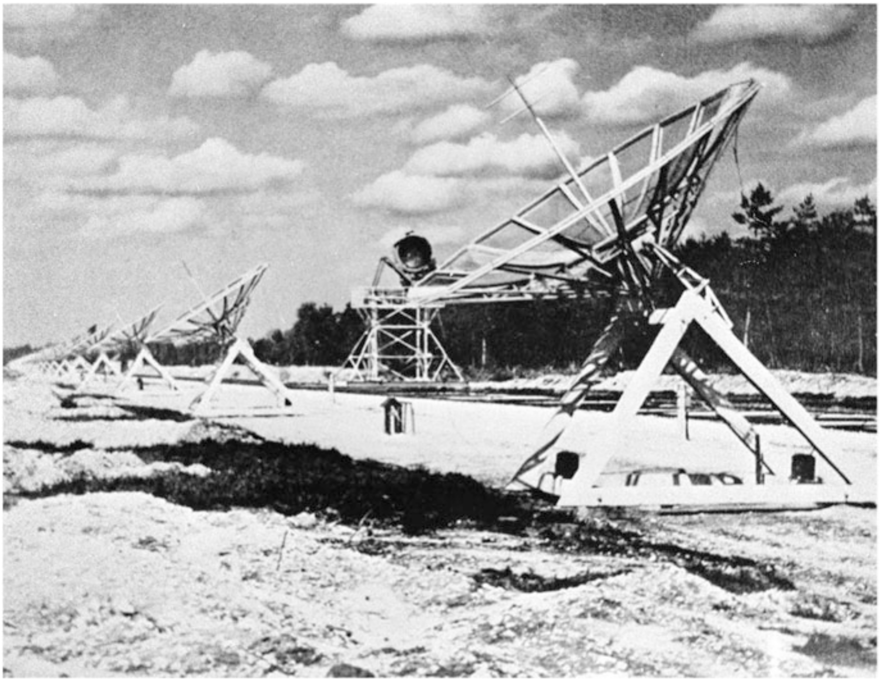

Fig. 7.1 A 32-element 169 MHz grating interferometer at Nancay in France inspired by Christiansen's design. Three different grating arrays were built at the Nancay field station operating at different frequencies for solar research (CSIRO Radio Astronomy Historical Photographic Archives B6480)

lines developed in Cambridge by Ryle's group. This ultimately became the Westerbork Synthesis Telescope which was inaugurated on 24 June 1970. Christiansen maintained an active collaboration with the Dutch group throughout the development of the new telescope. Together with Högbom, he wrote the classic book *Radiotelescopes*, which was published in 1969 by Cambridge University Press and later appeared in a Russian translation by Yuri Ilyasov in 1971 and a Chinese translation by Chen Jiansheng in 1977. A second updated edition was published in 1985. The experience gained in the development of the Westerbork Synthesis Telescope would significantly influence the design of subsequent synthesis telescopes including the Karl G. Jansky Very Large Array in New Mexico.

Similarly, the Mills Cross design was adopted by many groups. Bernard Burke from the Carnegie Institution of Washington in the USA built a cross array operating at 22.2 MHz in 1954 on a 96 acre field 20 miles northwest of Washington, DC (see Fig. 7.2). While testing the array in 1955, Burke and Kenneth Franklin discovered radio emissions from the planet Jupiter. Other large cross-type telescopes were also built in Italy, Russia and the Ukraine. While ideally suited to

Fig. 7.2 An aerial view taken in about 1954 of the Carnegie Institution of Washington "Mills Cross" radio telescope. The array is just visible running in a cross, diagonally across the field in the mid-ground. The cross operated at 20.2 MHz and was used by Bernie Burke and Kenneth Franklin to discover radio emission from the planet Jupiter, the first time radio emission was detected from a planet (Courtesy of the Archives of the Carnegie Institute)

single frequency survey work, the cross design ultimately gave way to more flexible arrays employing earth-rotational aperture synthesis and tracking dishes.[2]

The Australia Telescope

Without the foundations provided through the development of the Fleurs Synthesis Telescope (FST) and Molonglo Cross by the University of Sydney, it is unlikely that the Australia Telescope would have emerged. Both the FST and the development of the Molonglo Cross provided a rich breeding ground for young engineers and physicists to hone their skills working on real problems.

After his return from the Netherlands in 1962, Christiansen was contacted by Wild, following Pawsey's urging for greater collaboration, suggesting he apply for the transfer of the CSIRO Fleurs field station to the University of Sydney. Christiansen used this as an opportunity to launch the Fleurs Synthesis Telescope project as a basis for PhD projects and research. He clearly saw both the need for and benefit of involving engineers in the design and building of large complex

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[2] The large cross built by Mills at Molonglo was itself later adapted to use earth-rotational synthesis in its new form as the Molonglo Observatory Synthesis Telescope (MOST).

instruments that needed to push the boundaries of current technology to reach their performance goals. Many young engineers, who would go on to contribute both broadly and deeply, cut their teeth on this project. They would influence radio telescope development worldwide as well as reaching more broadly into areas such as the development of Wi-Fi.

One young graduate, Bob Frater, was offered a position in 1961 working on the Molonglo Cross by Ron Aitchison who was then an Associate Professor in Electrical Engineering at the University of Sydney. Mills's design for the Molonglo Cross presented many unique and difficult engineering challenges. Frater developed a number of key components for the new Cross. These included a transconductance multiplier, a critical component used to multiply together the signals from the two arms of the telescope and a synchronous integrator that allowed much better performance in the multiplication and integration of signals from the arms of the telescope, greatly increasing the dynamic range compared to previous systems which required the use of squaring and subtracting of responses. He also developed a precision phase metre necessary to calibrate the different delay line switching used in the Cross. Besides working on the Mills Cross and completing his PhD in 1967, Frater also took on responsibility for the electronic systems of the FST and made a key contribution to the correlator design of the Optical Stellar Interferometer being developed by Hanbury-Brown at Narrabri, New South Wales. During this period, he was heavily influenced by Mills, Christiansen, Bracewell, Wild, Hanbury-Brown and Alec Little. After working in industry with Amalgamated Wireless Australasia (AWA), Overseas Telecommunication (OTC) and Ducon, Frater recalled that going back to the University of Sydney was like being given his own special playpen, with sandpit and lots of toys. This was a time of infinite opportunity because of the state of electronics and the new technology that was under development. Effectively, Moore's Law was at "zero". The atmosphere was one where no attempt at anything was going to be laughed at and that encouraged "what-if" and "why-not" questioning. During this period, he also learned the "coding" of shorthand approaches from his mentors.

In 1981 Frater was recruited by Wild and appointed as chief designate of Radiophysics with the goal of rebuilding the division (see Fig. 7.3). Radiophysics had an illustrious history in radio astronomy, but during the 1970s, its reputation had slipped considerably. The Culgoora Radioheliograph had achieved most of its scientific goals, and the new frontiers of solar astronomy were moving to space-based observatories. The highly successful Parkes Radio Telescope had been in operation for over two decades and was being challenged by the new generation of synthesis telescopes. Large synthesis telescopes existed or were under construction in the UK, Netherlands, France, Japan, Canada and the USA. However in Australia, despite active discussions since late 1974, no concrete plans had emerged. A steering committee, chaired by Wild and including membership from the CSIRO and Australian Universities, was formed in 1975. Many options were considered, and eventually a modest system was proposed that would incorporate the existing Parkes radio telescope and would be called the Australian Synthesis Telescope

Fig. 7.3 Four generations of Chiefs of Radiophysics. Bob Frater (*left*) was the incoming Chief at Harry Minnett's (second to *left*) retirement in 1981 when this photograph was taken. Edward Bowen (*right*) was Chief from 1945 until he retired in 1971 and Paul Wild (second to *right*) took over the role. Harry Minnett replaced Wild in 1978 when Wild became Chairman of the CSIRO (CSIRO Radio Astronomy Historical Photographic Archives B12815-5)

(AST). Funding of the AST was ultimately turned down by the Australian government.

With the radio astronomy programme somewhat in the doldrums and the major industry programme, the Interscan microwave landing system also coming to an end, Wild sought to inject new life into the Division of Radiophysics. Frater put forward a proposal to the CSIRO Executive for funding a completely new major instrument, the Australia Telescope. Frater was determined, based on his experiences with both the FST and Molonglo Cross, not to underfund the development of the new instrument. He felt that the early proposals for the AST were not sufficiently ambitious to return the CSIRO to a position of leadership. In a master political stroke, he proposed the project be delivered as a Bi-Centennial programme to coincide with Australia's 200-year anniversary of English settlement in 1988. The project was initially funded in 1981 and, despite a subsequent change of government, managed to survive with full funding committed in 1983 (see Fig. 7.4).

The goal of the Australia Telescope project was to create a world-class instrument with 80% Australian content consisting of a compact array of six 22 m

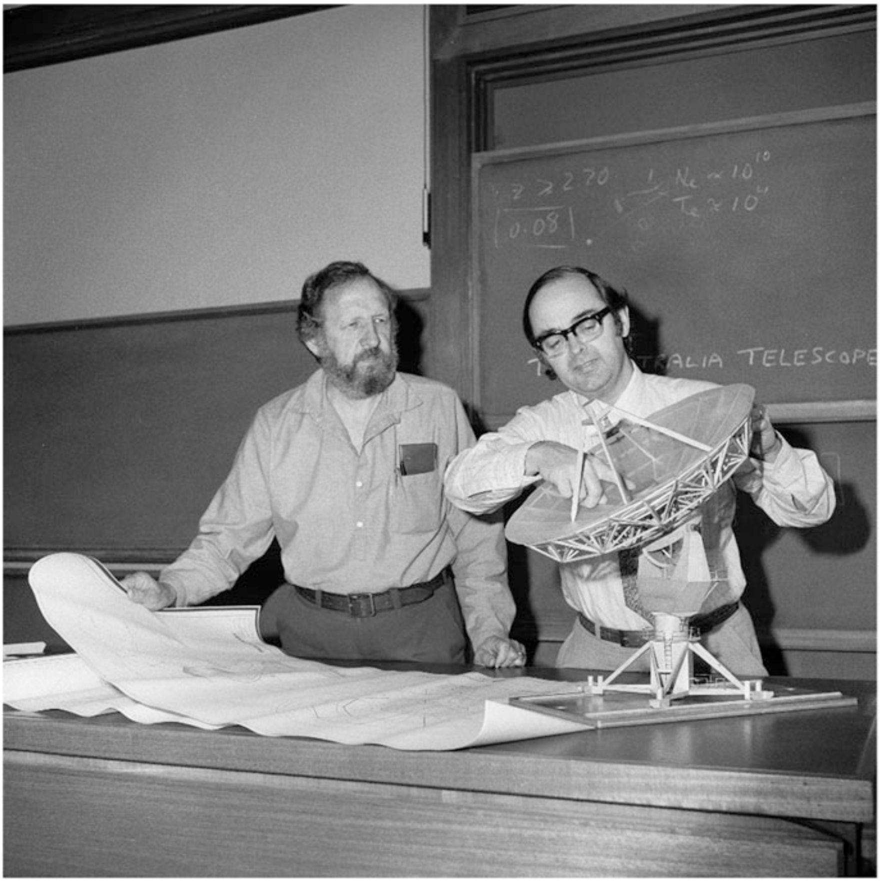

Fig. 7.4 Brian Robinson (1930–2004) and Bob Frater (*right*) discussing the design of the Australia Telescope in 1981 (CSIRO Radio Astronomy Historical Photographic Archives B12920-6)

antenna dishes arranged in a linear array with five of the dishes on a 3 km baseline railway track and a sixth antenna located a further 3 km to the west of the end of the main track located at Culgoora, later to be renamed the Paul Wild Observatory (see Fig. 7.5). A further single 22 m antenna was located at Mopra, 20 km to the west of Coonabarabran. Together with the Parkes radio telescope, this instrument could be used for long baseline interferometry.

Frater set out to draw engineers and scientists from around the world to the CSIRO. He attracted a number of expats, including Ron Ekers who was appointed Foundation Director of the Australia Telescope National Facility (ATNF). Dennis Cooper was appointed Assistant Chief and also took responsibility for the antenna design, with John Brooks as the overall Project Manager. During the development, industry contracts were awarded for the satellite ground station antenna design for Aussat and Galaxy multibeam antennas and the Overseas Telecommunication

Fig. 7.5 An aerial view of Culgoora in the mid-1980s showing the newly bulldozed path of the east-west track of the Australia Telescope Compact Array in relationship to the original Radioheliograph array. The westernmost station is the 6 km station of the Compact Array (CSIRO Radio Astronomy Historical Photographic Archives P14358-4)

(OTC) antennas at Gnangara, Australia, and Vietnam. Ultimately the Australia Telescope was delivered on schedule and officially opened on 2 September 1988 for a cost of a $50 million (see Fig. 7.6).

As a fitting tribute to their contributions, each of the *Four Pillars* was in attendance at the official opening of the Australia telescope: Bracewell (see Fig. 7.7), Christiansen (see Fig. 7.8), Mills (see Fig. 7.9) and Wild. Two of the authors were also present: Frater and Goss.

The Development of Wi-Fi[3]

Another graduate from the University of Sydney was John O'Sullivan who completed his PhD in 1974 using the Fleurs Synthesis Telescope. After graduation, he took an appointment in the Foundation for Radio Astronomy in the Netherlands (now ASTRON) and went on to become a leader in their receiver group taking over from Jean Casse. During his time in the Netherlands, he gained experience in two key areas. The first related to a procedure developed in optical astronomy for

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[3] This section has drawn heavily on material from a talk titled "The Role of Astronomy in Wi-Fi Technology" given by John O'Sullivan at a conference held on 13–17 September 2016 in Queenstown, New Zealand, during *Innovation and Discovery in Radio Astronomy: A Celebration of the Career of Ron Ekers*.

Fig. 7.6 Bob Frater speaking at the official opening of the Australia Telescope on 2 September 1988. Seated (L–R) are Hon. Neville Wran, former Premier of NSW and Chairman of the CSIRO 1986–1991; Hon. Bob Hawk, Prime Minister of Australia 1983–1991; and Hazel Hawke and Hon. Barry Jones, Minister for Science and Technology 1983–1990 (CSIRO Radio Astronomy Historical Photographic Archives N15191-9)

sharpening images distorted by the earth's atmosphere. O'Sullivan was a co-author of a paper (Hamaker, O'Sullivan, & Noordam, 1977) on the cancellation of phase errors induced in the atmosphere on the Westerbork Synthesis Radio Telescope (WSRT). They were able to show that the algebraic solution for redundant, or multiple measurements of the same baseline, was fundamentally equivalent to the maximising of image sharpness in optical imaging. The second related to a theory that had been developed in mid-1974 by Stephen Hawking (1974); he proposed that quantum fluctuations would allow black holes to produce radiation and that a small black hole could possibly explode. Martin Rees had proposed that the detection of such explosions would be possible as electromagnetic pulses at astronomical distances. Encouraged by Jean Casse, O'Sullivan was part of the group that attempted to look for these short duration bursts (O'Sullivan, Ekers, & Shaver, 1978). Initially they designed a simple double-tuned IF amplifier that was adjusted to give a double-peak frequency response rather than the normal smooth broad response. In this way, the frequency-swept radio pulse would generate a double time spike in the power detector, producing the characteristic signature of a dispersed pulse. The first pulse detection observations occurred at Dwingeloo.

Fig. 7.7 Ron Bracewell and Miller Goss at the official opening of the Australia Telescope. In the background is Helen Bracewell and to the *left* is Wim Brouw from the Netherlands (CSIRO Radio Astronomy Historical Photographic Archives N15178-19)

Fig. 7.8 Chris Christiansen (*left*) at the official opening of the Australia Telescope. To the *right* of Chris is Dorothy Goddard and seated at the table is the Engineer Keith McAlister and Ron Stewart of the Radiophysics solar group (CSIRO Radio Astronomy Historical Photographic Archives B15176-99)

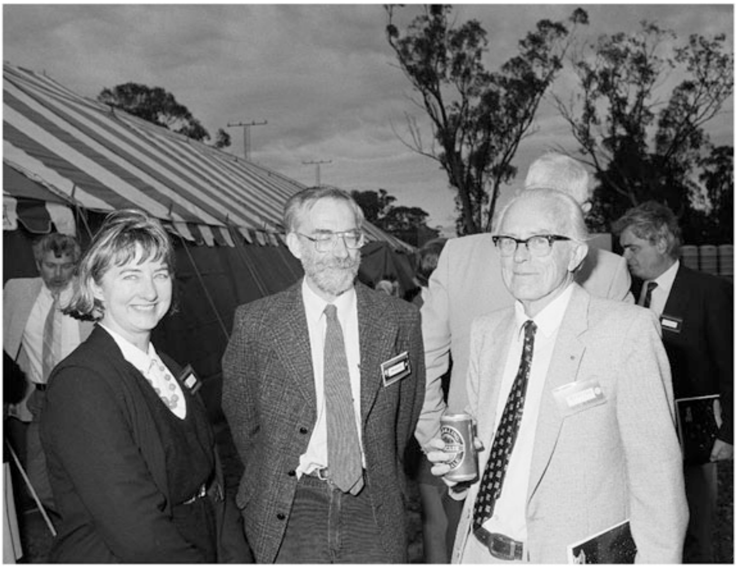

Fig. 7.9 Bernie Mills (*right*) at the official opening of the Australia Telescope with Penny Nelson and Mike Kesteven (CSIRO Radio Astronomy Historical Photographic Archives B15176-96)

They developed a laser-based acousto-optic spectrograph at Effelsberg based on a regular spectrograph but adapted to record on high-speed film. Using the full 14 × 25 m dishes of the WSRT as a tied array, the system produced hundreds of metres of film every few minutes, all of which needed to be examined inch by inch, looking for a characteristic faint V-shaped record. Although ultimately unsuccessful in detecting any pulses, the frustrating experience of having to manually examine the film records (see Fig. 7.10) inspired O'Sullivan to look at digital electronic alternatives, specifically, the development of special digital hardware to perform Fourier transforms. The coupling of the technique of the Fast Fourier Transform and reasoning similar to that for atmospheric phase correction and other imaging problems would later prove critical to the development of the multipath correction techniques used in Wi-Fi.

In 1983, O'Sullivan, recruited by Frater, returned to Australia to join the Division of Radiophysics to run the Signal and Imaging Technology Group. Frater encouraged the team to look to commercially relevant research where they could apply the skills developed in the fundamental field of radio astronomy. This group was involved in signal processing for medical imaging, geophysics imaging, mine safety and radar. One early project was the design of a Fourier transformation chip. The A41102 Fourier chip was produced in conjunction with the start-up Austek Microsystems, based in Adelaide. This firm had been spun off the CSIRO Very Large Scale Integration (VLSI) Chip Program developed by Craig Mudge in the mid-1980s. The FFT chip achieved only very limited commercial success in military and astronomical applications, including the XCELL correlator for the

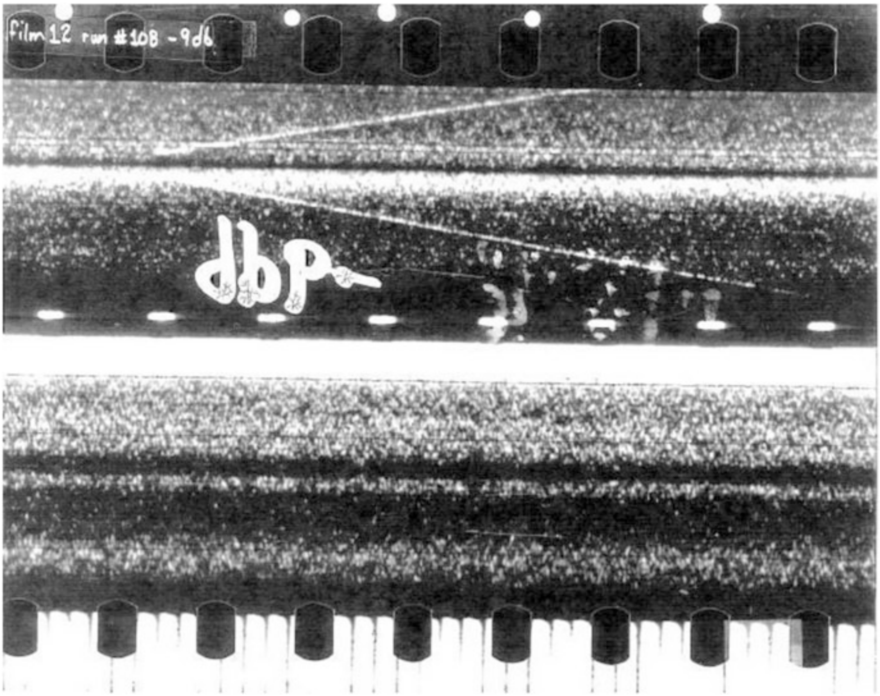

Fig. 7.10 An example of the film record produced by the acousto-optic spectrograph and film recorder. Having to examine hundreds of metres of these records caused John O'Sullivan to contemplate an alternative hardware Fast Fourier Transform (FFT) solution

Australia Telescope. Austek, however, initially did very well selling cache chips for the Intel 80386 processor used in personal computers, but these were later superseded when Intel built a cache into the processor. The ability to perform this type of high-speed processing in a more cost-effective manner turned out to be vital for the later development of Wi-Fi.

In 1991, Frater held a major strategy meeting to plan the research future of the group. At this meeting, O'Sullivan presented his Program for Local Area Network Systems (PLANS) using FFT techniques in wireless networks. O'Sullivan and team recognised that the key problem for wireless networks was to overcome interference from reflections of the radio signal from internal structures within a building. Dividing the signal into many narrow band signals using the Fourier transform chip had the effect of "stretching" the bits of information to a length that is large relative to the size of the signal reflections from the internal structures within a building. Hence, individual channels could be reconstituted without error. The wireless LAN patent (US5487069) by O'Sullivan, Terence Percival, Graham Daniels, Diet Ostry and John Deane (see Fig. 7.11) came out of this programme and would become the Institute of Electrical and Electronics Engineers (IEEE) standard 802.11a. Of the five inventors, three had started their careers working with Frater on the Fleurs

Fig. 7.11 The five inventors of the wireless LAN patent and Denis Redfern who played a key role in commercialisation (L–R): John Deane, Denis Redfern (not part of the original patent), John O'Sullivan, Diet Ostry, Terry Percival and Graham Daniels (Courtesy of John O'Sullivan)

Synthesis Telescope, three had worked with the Australia Telescope National Facility (ATNF) and all had worked on ATNF projects. They had individually worked on a diverse range of areas from satellite communications, local oscillator distribution systems, digital correlators, radar, Interscan microwave landing system, image processing, FFT chips and fast processing, electromagnetics and antenna design.

Frater had established a joint research centre with Macquarie University which proved important in later interactions with Dave Skellern. Skellern had originally completed his PhD working on the hardware design for direct transformation processing of rotational synthesis data from the FST (Skellern, 1985). In 1989, he took up the Chair of Electronics at Macquarie University. Skellern recruited Neil Weste, who was the co-author of the standard text on Complementary Metal-Oxide-Semiconductor (CMOS) VLSI design, and together with Terry Percival in 1997, they founded the company Radiata to commercialise the wireless LAN technology licenced from the CSIRO patent. Radiata demonstrated the first 802.11a 54 Mbps Wi-Fi chips in September 2000 and was acquired in 2001 by CISCO for approximately US$300 million.

At the heart of the story of the success of the development of Wi-Fi is the role that the people and environment involved in the advancement of radio astronomy had in nurturing this type of work. The leadership of the Division of Radiophysics, the *Four Pillars* and the next generation of leaders that they directly inspired contributed hugely to the environment that encouraged young engineers and physicists to try new techniques. This was the type of leadership that encouraged, guided, prodded and allowed the freedom to achieve the outstanding.

Imaging

The publication in 1965 of Bracewell's book *The Fourier Transform and its Applications* marked the end of a period of development that cemented the early "physical versus mathematical" learnings from Pawsey and the period with Ratcliffe. The book became the Fourier transformation "bible", not only for radio astronomers, but for engineers, physicists and medical researchers. Through it, Bracewell established a level of recognition for his elucidation of the convolution theorem and its importance in the interpretation of observations.

In the late 1960s, Bracewell's work on reconstruction of images from one-dimensional scans became recognised as having an important application in medical imaging by X-ray tomography. The theory of reconstruction of a two-dimensional image from one-dimensional scans had been explained by Bracewell (1956) and further advanced in the paper with graduate student A.C. Riddle (1941–2005) on "Inversion of fan-beam scans in radio astronomy" (Bracewell & Riddle, 1967). Bracewell wrote another paper specifically on tomography with graduate student J. Verley (Verley & Bracewell, 1979). He also devoted a chapter on tomography in his book *Two-Dimensional Imaging* (Bracewell, 1995). For his contribution to tomography, Bracewell was awarded associate membership of the Institute of Medicine of the US National Academy of Sciences in 1962.

Bracewell himself summarises the contribution of the early work on imaging theory in radio astronomy in his invited contribution to Sullivan's (1984) *Early Years of Radio Astronomy*:

> The splendid atmosphere at the Radiophysics Laboratory under the direction of E.G. Bowen and J.L. Pawsey and the stimulation of such colleagues as W.N. Christiansen, B.Y. Mills and J.P. Wild kept the mind occupied with good problems. If I seem to have quoted lots of my own papers, the fact is that while all the radio astronomers vigorously discussed their data processing problems, they wrote mostly about astrophysics and confined instrumental matters somewhat apologetically to introductions and appendices. A memorable exception would be J.P. Wild's papers of the following decade discussing the principle of the circular array at Culgoora. Looking back now we see that no apology was required for the instrumental and image formation aspects of radio astronomy in the fifties. Starting from modest beginnings and by small steps, radio astronomers took the separate field of antennas, receivers and information theory and welded them into image forming systems that have improved by seven orders of magnitude in resolution, surpassing the optical telescope, and inspired other developments in fields as diverse as optics, acoustics, seismic probing and X-ray tomography.

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Chapter 8
Conclusions

The *Four Pillars* established worldwide reputations as the leaders in their fields, and the instruments and techniques they developed have underpinned much of modern radio astronomy.

In hindsight, the fact that a country as small as Australia managed to support a relatively large scientific budget for research in radio astronomy is quite surprising.

Although there are some obvious examples of the practical spin-offs that have arisen from this fundamental research (Wi-Fi being perhaps the best example), the unsuspected fact is that the balance between fundamental and applied research did not tip quickly in favour of emphasising applied research. The success of the early research and the international reputation that came with it played a major role in the enhancement of this position. In a confidential report to the CSIR Executive Council dated 22 March 1943, Fred White outlined the role the Radiophysics Laboratory might play in the post-war period. He wrote:

> No scientific institution can flourish unless it is encouraged to participate in pure scientific research and maintain a close contact with, and an interchange of personnel with, the universities…It is difficult to assess the value of such work in terms of direct financial return to the community, but it may be judged by other scientists, by the standing and reputation of the work of the institution in relation to other purely scientific work throughout the world.

The CSIRO Radiophysics Laboratory environment proved excellent for allowing new ideas to blossom.

The *Four Pillars* and their mentors were systems thinkers: each had the capacity to hold and manipulate a complex image or concept in his head. They had the authority to implement decisions flowing from their deliberations on these concepts and were not blocked by people who were unable to grasp the broader issues. The dispersal of the original group provided a network effect that allowed their influence to spread. They contributed to the development of others through their advice, their encouragement and their maintenance and defence of those aspects of the work environment necessary for the development of new leaders.

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Bernie Mills invented the cross-type radio telescope that now bears his name. He contributed to the understanding of the nature of discrete radio sources. He had the courage to engage Martin Ryle of Cambridge, one of the giants of radio astronomy, in a dogged battle over the validity of the radio survey source count data that Ryle was using to determine which cosmologic model was correct: either the "Big Bang" or "Steady State".

Chris Christiansen invented and designed array-type telescopes. He was among the first to apply earth-rotational synthesis to produce high-resolution images. His influence, both direct and indirect, extended to the design of radio telescopes throughout the world.

Paul Wild was a master at joining radio observations and theory to elicit the nature of the solar atmosphere. He devised the major classifications for types of solar radio bursts that have stood the test of time and are still in use today as the standard. His work in solar radio astronomy dominated the field for over three decades.

Finally, Ron Bracewell is remembered for his contribution to the development of theory and mathematical techniques used to form images from radio observations. These techniques are the foundation of all of radio astronomy imaging today as well as having been extended to fields as diverse as medical imaging.

These men are pillars of radio astronomy who rose out of the rich, raw materials and management of the early days of Australian radio astronomy. We can look to them for lessons to ensure the future health and strength of world radio astronomy.

What are these lessons? The combining factors of the increasing cost of big science and political expediency in looking for quick returns from applied research are increasingly creating an environment removed from that experienced by the *Four Pillars* in their early years. Looking back, we can summarise five key ingredients for success in bringing new ideas to fruition:

(1) A clearly identified existing or emerging need
(2) A champion, someone with fire in their belly and a clear view of the goal
(3) Mentors who provide example and guidance
(4) A supportive environment with the availability of resources, both material and intellectual, as well as people with systems-thinking ability and physical understanding
(5) Finally, a sponsor, someone in a position to help, who appreciates and supports the goal

To have all of these ingredients is a great gift. There are, of course, examples of people who have still succeeded against all odds, but these are rare.

The key questions for the future are: Are we working to have such environments exist in the future? Are we identifying and developing the next generation of systems thinkers? How do we protect our systems thinkers in the future in an increasingly bureaucratic world?

Certainly the new discipline of radio astronomy, as it developed in the first decade after World War II, benefited by the innovations and leadership of the *Four Pillars*. Their influence has continued well into the twenty-first century.

Appendix A: What Is a Radio Telescope?

A radio telescope is similar to an optical telescope; however, instead of gathering light, the instrument gathers radio waves. Radio waves from space have a much longer wavelength than light, so radio telescopes need to be much larger than optical telescopes to achieve a similar resolution. "Resolution" is a description of the ability to distinguish between two closely spaced sources. The size of the collecting area of the telescope also governs its sensitivity, which determines the ability to detect weak radio signals.

The terms radio telescope and aerial (or antenna) are often used interchangeably. Radio telescope may also refer as well to the whole system, including the receiving and signal processing systems.

Dipole Aerials

The most basic type of radio telescope is a simple dipole linked to a receiver. A dipole is a pair of metal rods that collect the radio signal, with a size of half a wavelength. The half wavelength is used because this length has a natural resonance to the radio waves which excite electrical currents in the metal rods. This electrical signal is then amplified in a receiver and passed to a display or recording system. Most early radio telescopes used a simple paper chart recorder to record the intensity of the received signal as a function of time.

Dipoles are often used in conjunction with a set of director rods, which are slightly smaller, and a reflector rod which is slightly larger. These "director" and "reflector" rods help focus the radio waves on the receiving dipole. The Yagi-Uda aerial was invented in 1921 by two prominent Japanese electrical engineers, Hydetsugu Yagi (1886–1976) and Shintaro Uda (1896–1976), often simply referred to as a Yagi aerial. This type of aerial will be familiar to the reader as the type used on household rooftops to receive analogue TV signals (see Fig. A.1).

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Fig. A.1 A Yagi-Uda aerial commonly used to receive analogue TV signals. The first three rods are directors which are slightly smaller than the half-wave length receiver rod. The final rod is the reflector, which is slightly larger. The cable leading from the dipole rods to the receiver is visible (Source: Wikipedia)

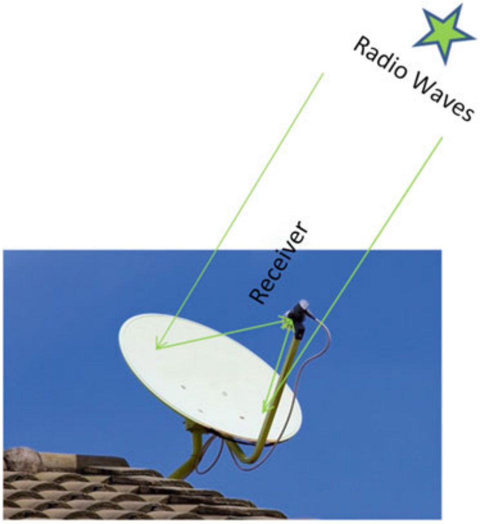

Fig. A.2 A basic "dish"-type aerial. This aerial collects the incoming radio waves and focuses them on a receiver. This antenna is the same type of aerial used for satellite TV dishes

Dipole arrays can be used in many different configurations. When installed with reflecting backing screens, the aerial is referred to as a "broadside" array.

The first radio telescope was used by Karl Jansky in the early 1930s and was a complex type of dipole array called a Bruce Curtain aerial (see Chap. 2, Fig. 2.2). The dipoles were large as the observing wavelength was 14.6 m (frequency 20.5 MHz).

Dish Aerials or Antennas

Perhaps the most familiar type of aerial is the dish type which is also used for satellite TV antennas. The dish reflects the incoming radio wave to a receiver at the focal point of the parabolic shaped dish (see Fig. A.2), an analogue of a reflecting optical telescope.

The resolution of the dish-type radio telescope is dependent on the diameter of the dish being used and must be larger than the wavelength of the radio waves being observed: the bigger the dish, the better the resolution. The diameter of the dish is referred to as the aperture, with the dish being a type of filled aperture telescope.

This aerial was the type of radio telescope built by Grote Reber in 1937 (see Chap. 2, Fig. 2.3). One of the benefits of the dish aerial is that it can be used to observe at different frequencies simply by changing the receiver at the prime focus of the aerial.

Like optical telescopes, most dish-type radio telescopes have a mounting that allows them to track a source as it moves across the sky due to the rotation of the

Fig. A.3 The Five-hundred-metre Aperture Spherical Telescope (FAST) in China. The receiver is suspended at the prime focus point by cables from the surrounding towers. It began observations in September 2016 (Credit Xinhau) earth. Unfortunately, there is a structural size limit (~100 m) in the construction of large dish-type aerials; for such structures, gravity distorts the surface of the dish, limiting the high-frequency use of the antenna as the astronomical object moves over the sky. To overcome some of these limitations, the largest dish-type radio telescopes, such as the recently commissioned Five-hundred-metre Aperture Spherical Telescope (FAST) built in China, are fixed in place (see Fig. A.3). FAST was built in a natural sinkhole in the ground pointing straight up, relying on the earth's rotation and the active adjustment of reflector panels and receiver feed point to observe a limited portion of the sky. This instrument also uses a spherical reflecting surface for simplicity of construction rather than a parabolic surface.

Beamwidth of a Radio Telescope

All aerials have directional sensitivity. A dipole is most sensitive when the rods are at right angles to the incoming wavefront; however, the sensitivity is bidirectional and so reflectors are used to reduce unwanted signals. A dish is naturally unidirectional and most sensitive when pointed directly at the radio source. The electrical response of the incoming radio waves can be measured by the dish. The aerial response pattern is referred to as the beam pattern or lobe response. The beamwidth is normally defined as the angular distance between two points either side of the maximum response where the signal falls to half of the maximum power. A small dish operating at metre wavelengths will have a beamwidth of a few tens of degrees. This limitation implies that the aerial cannot distinguish between two point sources that fall within a single beamwidth.

Units of Measurement

A radio telescope can measure the angular position in the sky of a radio source, the angular size and the received intensity of the radiating source. The intensity of the source is called the flux density and is a measure of power for a given range of wavelengths, per unit of surface area at the receiving telescope. The unit of flux density is watt per square metre per unit frequency bandwidth (in Hertz) and is written as $\mathrm{Wm}^{-2}\ \mathrm{Hz}^{-1}$. In honour of Karl Jansky, this standard unit is now called a *Jansky* (J). One *Jansky* is equivalent to $10^{-26}\ \mathrm{Wm}^{-2}\ \mathrm{Hz}^{-1}$. The strongest observed radio sources from space typically have flux densities in the order of 1–100 J. In comparison, the signal from a mobile phone placed on the moon (a mobile phone has a transmission power of about 1 W at a frequency of 1.8 GHz) would produce a flux density of about 1.45 J as measured on the earth's surface. Thus, a mobile phone on the moon would produce an easily detected signal.

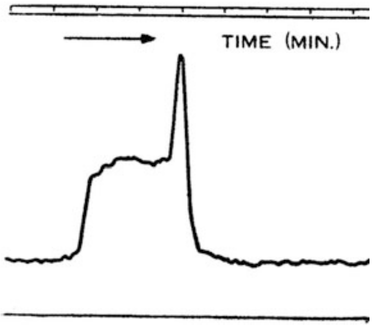

Fig. A.4 An example of a chart recording of the intensity of radio waves from the sun at a wavelength of 21 cm. In this example, the sun is moving through the aerial beam as the earth rotates. The *Y-Axis* shows the intensity of the received signal, and the *X-axis* is time marked in minute intervals. The intensity increases as the sun enters the aerial beam. In this instance, there is a strong source of radio emission produced above a sunspot group on the western side of the sun. The intensity increases markedly as the sun moves outside the aerial beam. In this example, the beamwidth of the aerial was about 3 arcmin. The diameter of the sun is 30 arcmin. The radio emission arises from the sun's outer atmosphere: the diameter of the radio source is slightly larger than the optical size of the sun. The transit time of the radio sources is about two arcminutes (after Christiansen & Warburton, 1953)

A radio telescope can also measure the intensity of radio sources at different wavelengths (or frequencies). This procedure allows the astronomer to measure the radio spectrum of a source, intensity versus frequency. The radio spectrum of a radio source provides useful clues as to the nature of the physical process producing the radiation. Certain types of aerials which are responsive to broad ranges of frequencies, such as a rhombic aerial,[1] are used when measuring multiple frequencies.

Radio Images

In an optical telescope, light is focused to a point so that the detector can be used to derive an image of the astronomical object. A radio telescope measures the intensity (flux density) of the received radio waves from a given area of the sky. In early radio astronomy, this intensity was represented as a recording on a paper chart recorder (see Fig. A.4). The paper on the chart recorder was moved at a steady rate while the pen moved in response to changes in the intensity of the received signal as a function of time.

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[1] A rhombic aerial uses one to three parallel wires suspended above the ground in a diamond shape, supported by poles or towers at each vertex to which the wires are attached by insulators. Each of the four sides are the same length, typically at least one wavelength or longer.

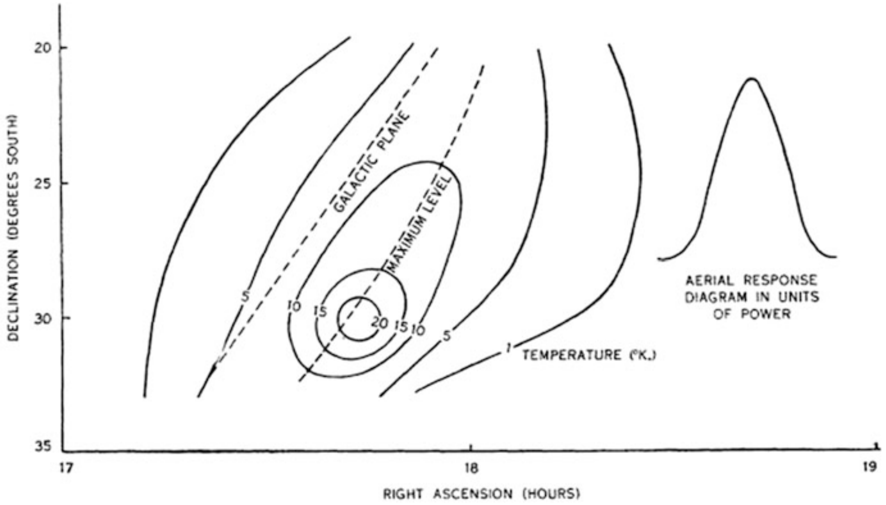

Fig. A.5 An example of an early contour diagram showing the intensity of radio waves from the Galactic centre. This contour image was produced by scanning the aerial beam across the sky and recording the intensity observed in the parts of the sky that fell within the aerial beam (after Piddington & Minnett, 1951). *Right* ascension is the astronomical longitude coordinate, and declination is the astronomical latitude. The aerial beamwidth at 1210 MHz was 1.4°

By measuring the intensity across different areas of the sky, it is possible to build a contour diagram of the intensity of the radio waves being received. The contour diagram is effectively an image of what the radio telescope is seeing. The higher the resolution of the telescope, the more detail can be produced in the image (see Fig. A.5).

Radio Interferometers

Due to the physical size limitations and complexities of building large single-dish radio telescopes, radio engineers invented a technique to improve the resolution of a radio telescope without increasing the dish's size. This technique relied on a method invented at the end of the nineteenth century by Albert A. Michelson, the "Michelson interferometer". While principles of interferometry were well understood by optical astronomers such as Michelson, the technique was first introduced into radio astronomy in 1946, based on the experiences of radar scientists during WWII.

By using two aerials spaced at a distance and connected to a common receiver, the radio astronomers could achieve comparable angular resolution as a filled aperture telescope which was equivalent in size to the spacing between the individual aerials (see Fig. A.6). While not as sensitive as a filled aperture telescope, the same resolution was achieved at a much reduced complexity and cost. This type of radio telescope is referred to as an *interferometer*. The farther the spacing between

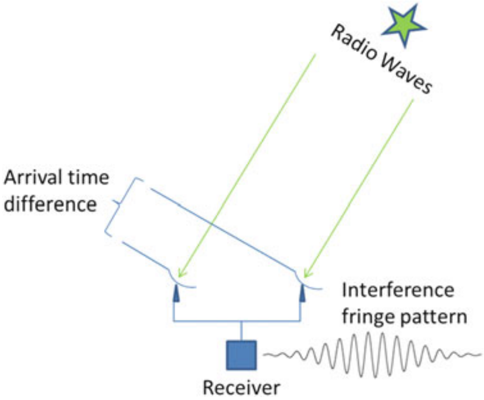

Fig. A.6 The radio waves arrive at the aerials at slightly different times. This phase difference creates a pattern of interference fringes in the combined signal. The spacing of the fringes is determined by the spacing between the aerials and produces a resolution equivalent to a filled aperture the same size as the spacing between the aerials

aerials, the higher the resolution achieved. The only limitation on resolution is the maximum spacing that can be used while still obtaining a very accurate measurement of the signal path distance between aerials so that signal phase can be accurately determined. In the early years of radio astronomy, this was difficult for baselines longer than a few hundred metres. By the early 1950s, the use of radio-links helped overcome some of the limitations of physically connecting aerials. Later, with the invention of atomic clocks to synchronise measurements separately recorded, longer baseline instruments could be constructed. For example, the Very Long Baseline Array in the USA has a maximum baseline of 8000 km, comparable to the diameter of the earth (12,742 km). In the last few decades, both Japan and Russia have built spacecraft radio telescopes that have achieved baselines in the range 20,000–350,000 km. The resolutions achieved using these with earth-based baselines can far exceed that of the very largest optical telescopes, up to 0.3 milliarc seconds (the moon’s diameter of 30 arcmin is 1.8 million milliarcseconds in size).

In a simple two-aerial interferometer, the radio wavefront arriving at each dish will have a slightly different time of arrival at each aerial causing a phase difference between the arriving signals. When the signals are in phase, they will constructively interfere and when they are exactly 180° out of phase they will destructively interfere producing an interference fringe pattern.

The interference fringes are equivalent to having many small beams produced within the envelope of the beamwidth of a single aerial (see Fig. A.7). The resolution of the interferometer is a function of the fringe spacing; the larger the spacing, the narrower the fringe pattern and hence the higher the resolution.

Sea-Cliff Interferometer

In Australia, a technique of creating an interferometer using only a single aerial was developed in early 1946. This technique was based on experience gained with radar reflections from aircraft during WWII. By mounting the aerial on a cliff top

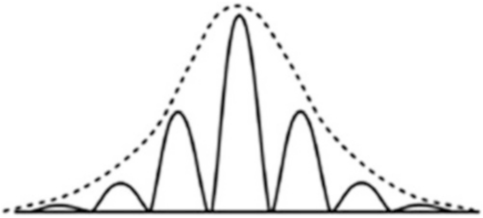

Fig. A.7 The beam pattern of a single aerial is represented by the *dotted line*. For a small aerial, the beamwidth would be some tens of degrees. Where two identical small aerials are connected as an interferometer and separated by several hundred metres, the difference in the phase of the signals causes an interference pattern. This effect produces a pattern of interference fringes falling within the overall aerial beam pattern. Each fringe is equivalent to a narrower beamwidth beam of a few tens of arcminutes, enabling higher resolution measurements. The *Y-axis* is the sensitivity, and the *x-axis* is the displacement in angle on the sky

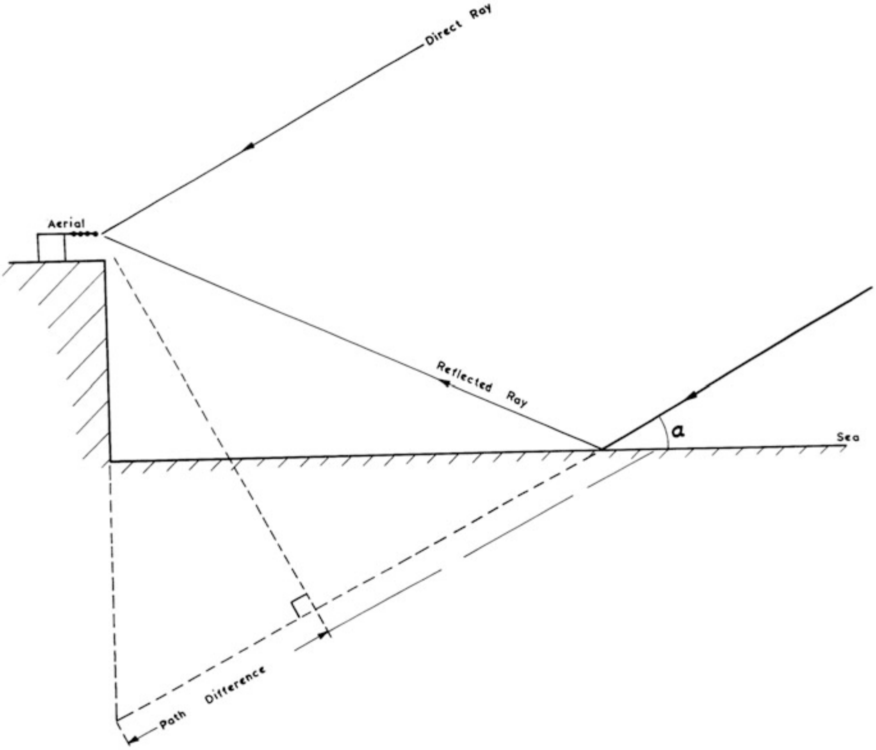

Fig. A.8 By observing both the direct radio waves from the source and the reflected ray from the sea, an interferometer using a single aerial was created. This system was equivalent to having two aerials spaced at a distance of twice the cliff height. At Dover Heights in Sydney's eastern suburbs, the cliffs were 85 m in height overlooking the sea and observing rising radio sources (first the sun and later discrete radio sources) over the eastern horizon, an interferometer was created. The principle used interference from the direct radio radiation from the astronomical source with the waves reflected from the sea surface. This created an interferometer with an equivalent spacing between aerials of twice the cliff height (85 m). A sketch of the sea-cliff interferometer is shown in Fig. A.8. Even though only a single aerial was required, numerous disadvantages were encountered. The baseline of the interferometer could not be varied. In addition, the low elevation of observation implied that the refraction of the radio waves was substantial and variable from day to day, with resultant uncertain positional determinations. The Australian group did succeed in 1947 in finding higher cliff sites in New Zealand and were also able, for the first time, to observe radio sources as they set in the west. Based on all these handicaps, within a few years the sea-cliff interferometer was discontinued, replaced by Michelson interferometers and arrays of antennas (see below).

The Mills Cross

Connecting a series of simple dipoles in a linear array produces a narrow beam; for example, a long east-west array produces a narrow E-W beam, a fan beam. If two linear arrays in the form of a cross are connected with the individual outputs combined, a narrow beam response is produced at the intersection of the two fan beams. The resolution is equivalent to that of a dish with the same diameter as the dimensions of the cross array (see Fig. A.9). This radio telescope was a cost-effective way of building a very large high-resolution radio telescope. The major limitation was the fact that the telescope could only be used at a single frequency, compared to the frequency agility of a single dish. In addition, the sensitivity was much less than that of a single dish of the same dimensions.

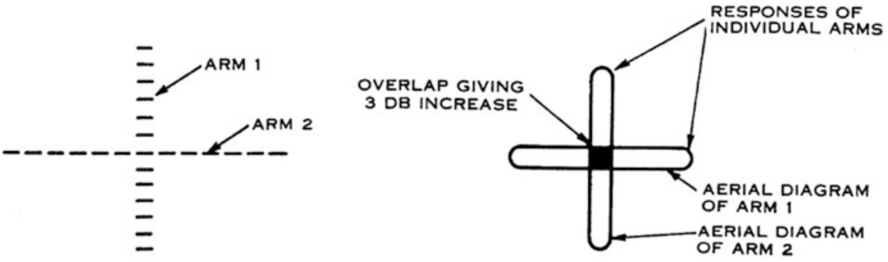

Fig. A.9 An illustration of a Mills Cross. The *left diagram* shows the arrangement of dipoles in each arm of the cross. The diagram on the *right* illustrates the aerial beam responses of the individual arms which are multiplied to produce a narrow pencil beam response. This system was the first prototype cross built at Potts Hill in the western suburbs of Sydney. Each arm was 36.6 m in length and operated at 97 MHz (3 m wavelength) producing a pencil beam with a beamwidth of 8° (after Mills & Little, 1953). After the successful prototype, a cross with arms of 450 m was built at Fleurs field station to the west of Sydney

The Grating Array

By combining the signals received from a linear array of many small dish aerials, an aerial beam pattern consisting of a series of narrow fan beams (see Fig. A.10) can be produced. This radio telescope is analogous to an optical diffraction grating; thus, the grating array was created. The length of the array and spacing between the individual aerials determines the beamwidth of each fan beam.

A crossed-grating array combines the features of the grating array with that of a Mills Cross, producing a series of intersecting fan beams that present a grid of high-resolution responses. This crossed-grating array was also sometimes referred to as a "Chris Cross" after its inventor, W.N. "Chris" Christiansen.

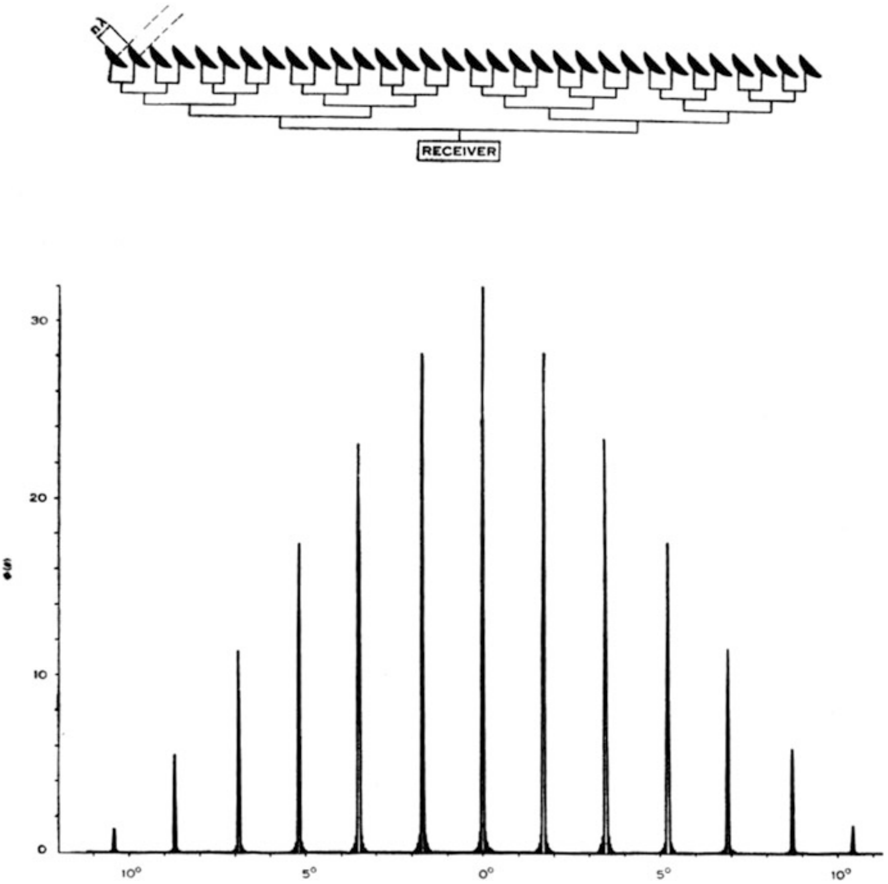

Fig. A.10 An example of a grating array using 32 aerials with a 217-m baseline (*top*). This configuration produced an aerial response (*bottom*) as a series of fan beams with a 3 arcmin beamwidth and a spacing of 1.7° between beams. The *Y-axis* shows sensitivity with arbitrary units and *X-axis* the beam pattern in degrees (after Christiansen & Warburton, 1953)

Aperture Synthesis Telescope

An aperture synthesis telescope is a more complex type of interferometer, based on an array of telescopes, sometimes in a linear array, or in other configurations such as a T-shape or Y-shape. By combining the signals received at a variety of different possible spacings between individual telescopes, a high-resolution image can be reconstructed. The mathematical technique of the Fourier transform is used to reconstruct the image based on the sampled interference fringes. The technique also makes use of the rotation of the earth to achieve measurements over a period of time from a variety of different angles as the source moves across the sky. This combination results in an improved sampling of the interference fringes, leading to an improved image quality (see Fig. A.11). All modern synthesis radio telescopes make use of this technique.

Martin Ryle received the Nobel Prize in Physics in 1974 for his perfection of the technique of aperture synthesis. The use of this technique for imaging became practical with the advent of digital computers to perform the Fourier transforms required to produce images. In 1955, Christiansen and Warburton produced a two-dimensional image of the quiet sun using the earth-rotational synthesis technique. Nearly 6 months of manual calculations were required to produce a single image since a suitable digital computer was not available. For this reason, the Australian group did not pursue earth rotational synthesis until the several decades later.

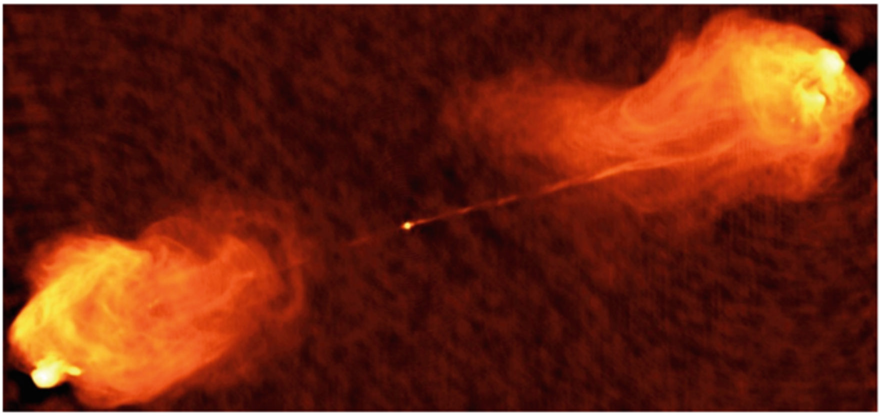

Fig. A.11 An image produced in 1983 by the technique of aperture synthesis using the Karl G. Jansky Very Large Array of the National Radio Astronomy Observatory in New Mexico. The radio source is Cygnus A. The compact source at the centre is radio emission associated with a central black hole. The galaxy is at a distance of 600 million light years. The field of view is 2.3 × 1.3 arcmin, and the image has a resolution of 0.5 arcsec (courtesy of NRAO/AUI). The radio waves are coming from electrons propelled at nearly the speed of light through a long, thin "jet" at the core of the galaxy and deposited in giant "radio lobes"

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Appendix B: Paul Wild: The Beer Disaster of November 1957

Paul enjoyed telling the story of Richard Twiss (1920–2005) from events in 1957. Richard Q. Twiss was a brilliant and eccentric UK astronomer who worked for a period at the CSIRO Division of Radiophysics in the 1950s. Later he joined Hanbury-Brown (1916–2002) at the University of Sydney, School of Physics in the 1960s, working on the Narrabri Stellar Intensity Interferometer; the eponymous Hanbury-Brown–Twiss effect from the mid-1950s is named after these two colleagues. In Sydney, Twiss was universally respected; he was often characterised as a "caricature of an Englishman".

In 1957 during the week of 25 November, as was the usual habit, numerous colleagues from the Radiophysics Lab crossed the City Road at 5 pm to rush to the nearby public house (pub), the Lalla Rookh.[2] The infamous 6 o'clock closing still existed; the scientists from the CSIRO labs and the Sydney University academics (men only) had to compete for accelerated service of beer with the New South Wales Government Railroad personnel from the nearby Redfern railyards. Each of the Radiophysics colleagues would take turns, as one by one would have their "shout" (for the non-Australians this meant to purchase drinks for all during the next "round") before the dreaded closing. On this day, close to 6 pm, Paul Wild was to shout his mates; he returned with two hands overflowing with numerous glasses of beer. As he turned around, he bumped into a burly engine driver with coveralls. All the glasses spilled into the coveralls. Paul tells the story that the large victim looked him over as he was about to flatten the startled scientist with his large fists. But, he looked at the fearful intended victim and began to laugh. At this point, Richard Q. Twiss appeared, the man to the rescue. In a very English upper-class accent, he said to the chastised Paul: "*I say Wild, trouble with the natives?*" All laughed; fortunately for Wild, the engine driver joined in.

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[2] Apparently named after the last surviving full-blooded Tasmanian aboriginal, Truganni (circa 1812–1876). She was also known as Lalla Rookh.

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This story was told time and time again in subsequent decades. Campbell Wade[3] arrived at Radiophysics on 1 December 1957 from the USA by ship. He worked as a postdoc (recently a PhD from Harvard) with Joe Pawsey at the Potts Hill field station, staying exactly 2 years before returning to the USA. Cam has reported, "In December 1957, nobody would talk about anything but that event….The participants had expected the railroad personnel to tear the place apart…But everyone just went back to drinking as all laughed".

Almost 10 years later, Goss arrived in Sydney as a postdoctoral fellow at CSIRO. The despised 6 o'clock closing law had ended a few months earlier. A few days after arrival, Radhakrishnan ("Rad") invited Goss to go across the street to the successor pub (the Lalla Rookh had been demolished) at 5 pm, now with a relaxed schedule. Goss was intimidated to be in the presence of famous radio astronomers: Wild, Steve Smerd, Kevin Sheridan, Norm Labrum, Rad, Max Komesaroff, etc. Within a few minutes as they sat down, the "natives" story was recounted by one of the other participants; the "new boy" had to hear the illustrious history of the Lalla Rookh.

A year earlier in 1966 (20 April), Paul Wild had written Peter Scheuer at the Cavendish Laboratory in Cambridge.[4] The main topic of the letter was to ask Scheuer's opinion of a prospective predoctoral visit to Sydney from Cambridge. At the end of the letter, Paul concluded:

> The only other news of note is the strong rumour that the explosive expansion of Sydney University will cause its shock wave to demolish the Lalla Rookh within a month. So ends an era. There will be no more trouble with the natives.

The "natives" story had a long life.

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[3] Interview with Goss in Socorro, New Mexico, USA, on 11 January and 25 January 2007. Wade described an American's first impression of the Australian pub: "Good Australian fellowship, lots of drinking and everyone talking in a loud voice! The women had to go to the lounge bar where the beer was slightly more expensive".

[4] From the Division of Radiophysics Archive (letters to Scheuer). Peter Scheuer was well known in Sydney since he had visited Radiophysics for three years starting in January 1960. In the letter, Paul also pointed out that Twiss had often referred in a joking manner to the "observationalists" at Radiophysics as the "idiots".

Appendix C: Supercomputing Cluster

In recent years, the CSIRO has named a line of supercomputers after prominent Australian Scientists in the CSIRO Division of Radiophysics whose pioneering work established the foundations of Australian Radio Astronomy. In July 2017, a new supercomputer cluster was commissioned by the CSIRO and named *Bracewell* as a way of honouring the scientific contributions made by Ron Bracewell during his career. The *Bracewell* cluster consists of 114 Dell PowerEdge C4130 rack mounted servers and is capable of performing 1 petaflops floating point operations per second. The cluster will be used for a variety of science projects that have high computation needs including radio astronomy, as well as providing machine learning and deep learning software platforms that underpin the emerging data-intensive sciences. In 2014, the supercomputer centre in the Perth suburb of Kingston, Western Australia, supporting the Square Kilometre Array (SKA), was named the *Pawsey Supercomputing Centre*.[5] This centre was appropriately named for J.L. "Joe" Pawsey, the "Grand Old Man of Australian Radio Astronomy" (see Chap. 2). Previous supercomputers have been named *Ruby*, after Ruby Payne-Scott, one of the original pioneers and the first female radio astronomer (from 1944); *Bowen*, after Taffy Bowen who was chief of the Division from 1946 to 1971; and Pearcey after Trevor Pearcey, who designed and developed CSIRAC, Australia's first programmable digital computer, and one of the first digital computers in the world.

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[5] The Pawsey Supercomputing Centre is an unincorporated joint venture between CSIRO, Edith Cowan University, Murdoch University and the University of Western Australia.

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Appendix D: Time Line of Key Events

1926	Council of Scientific and Industrial Research (CSIR) established.
1939	Radiophysics Laboratory (RPL) established with D.F. Martyn as Chief of Radiophysics, P.V. Madsen Chair of Radiophysics Advisory Board and J.L. Pawsey hired into Radiophysics.
1942	F.W.G. White takes over as Chief of Radiophysics from Martyn and remains until 1945.
1942	B.Y. Mills joins RPL.
1943	R.N. Bracewell joins RPL to work with Pawsey until Bracewell goes to England in 1946 to complete his PhD.
1945	J.N. Briton becomes Chief of Radiophysics until 1946. Pawsey becomes leader of the team investigating sources of "thermal and Cosmic" noise marking the beginning of the Radio Astronomy group in Australia. The first successful experiment in Australia occurred at sunrise on 3 October 1945 at Collaroy Plateau using one of the RAAF radars.
1946	E.G. "Taffy" Bowen takes over as Chief of Radiophysics, remaining as Chief until his retirement in 1971. The first Australian paper on radio astronomy by Pawsey, McCready and Payne-Scott published in *Nature*.
1947	J.P. Wild joins RPL.
1948	W.N. Christiansen joins RPL. The November 1948 partial solar eclipse observations mark entry of Mills and Christiansen to radio astronomy. Penrith field station established where Wild begins solar burst spectrum observations.
1949	CSIR reorganised into Commonwealth Scientific and Industrial Research Organisation (CSIRO). Bracewell returns from the UK to work at CSIRO (again). Mills and Thomas propose tentative source identification of Cygnus A, which subsequently proves correct, but are dissuaded by R. Minkowski from publishing.
1950	Christiansen builds first grating array telescope at Potts Hill. Wild proposes the classification of solar radio bursts into three classes: Type I, II and III based on his work at Penrith.

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1951	Christiansen and J. Hindman confirm detection of 21-cm Hydrogen line.
1952	International Union for Radio Science (URSI) meeting held in Sydney showcasing the achievements of Radiophysics. Mills proposes two-class distribution of discrete radio sources: one Galactic and the other isotopically distributed. This marks the beginning of controversy with Cambridge.
1953	Mills Cross prototype tested at Potts Hill; Fleurs field station established and construction of Mills Cross begins; north-south array added to solar grating array at Potts Hill.
1954	Observations begin using Mills Cross at Fleurs. Wild establishes Dapto field station. Pawsey elected Fellow of the Royal Society. Bracewell accepts lectureship to the University of California, Berkeley, from September 1954 to June 1955 at the invitation of Otto Struve.
1955	*Radio Astronomy* published by Pawsey and Bracewell. Bracewell moves to Stanford and joins Electrical Engineering faculty in December 1955. Christiansen publishes first use of earth-rotational synthesis to produce 2-D image of the sun.
1957	Chris Cross built at Fleurs.
1959	18 m Kennedy Dish added to E-W arm of Chris Cross to become the Fleurs Compound Interferometer. In 1962, the Kennedy Dish moved to Parkes.
1960	Mills moves to Department of Physics and Christiansen to Department of Electrical Engineering, University of Sydney.
1960	Bracewell builds Stanford Microwave Spectroheliograph.
1961	Frater joins Dept. of Electrical Engineering, University of Sydney.
1961	Parkes 64 m Radio Telescope opens (also known as the Giant Radio Telescope GRT).
1962	Pawsey leaves Radiophysics for NRAO, dies 30 November 1962. Funding grant approved by National Science Foundation (NSF) to commence work on Molonglo Cross. Ford Foundation provides initial funding grant for Culgoora Radioheliograph.
1963	Fleurs field station transferred to the University of Sydney; the Chris Cross would be the foundation for the development of the Fleurs Synthesis Telescope. Christiansen's first visit to China. Mills elected Fellow of the Royal Society.
1965	Molonglo Observatory opened by Prime Minister of Australia, Sir Robert Menzies on 19 November 1965.
1967	Molonglo Cross fully operational. Culgoora radioheliograph operational.
1969	*Radiotelescopes* by Christiansen and Högbom published.
1970	Westerbork Array opens in the Netherlands. Wild elected Fellow of the Royal Society.
1971	Wild takes over from Bowen as Chief of Radiophysics.
1973	Fleurs Synthesis Telescope begins limited observations and continues to be developed throughout 1970s.
1976	Mills appointed Companion in the Order of Australia.

1978	Molonglo Observatory transitions to Molonglo Observatory Synthesis Telescope (MOST). Wild appointed Chairman of CSIRO until his retirement in 1985. Minnett appointed Chief of Radiophysics. Christiansen becomes President of URSI until 1981. Wild appointed Commander of the Order of the British Empire (CBE).
1979	Bracewell retires. Christiansen retires.
1981	R.H. Frater becomes Chief of Radiophysics following the retirement of Minnett.
1984	Culgoora Solar Observatory closed.
1985	Wild retires from CSIRO. Mills retires.
1986	Wild appointed Companion of the Order of Australia.
1988	Australia Telescope opened by the Prime Minister of Australia, Hon. Bob Hawk. Fleurs Synthesis Telescope closed down.
2017	UTMOST opened, the University of Swinburne modification of the Molonglo Observatory Synthesis Telescope (MOST) for fast radio burst (FRB) survey.

Appendix E: Dramatis Personae for *Four Pillars of Radio Astronomy*

Bok, Bart (1906–1983) Dutch-American astronomer whose primary research interest was the structure of the Milky Way; career was at Harvard, Mt Stromlo (Canberra, Australia) and the University of Arizona

Bolton, John (1922–1993) British-Australian astronomer who identified first known radio galaxies together with Gordon Stanley and Bruce Slee. He established Owens Valley Observatory in California and was later the first Director of the Parkes Radio Telescope in Australia

Bowen, Edward G. "Taffy" (1911–1991), British born in Wales, member of the group headed by Sir Robert Watson Watt who developed British radar in 1935; member of Tizard Mission from the UK to the USA in 1940; Radiation Laboratory Massachusetts Institute of Technology until 1943; CSIR and later CSIRO Division of Radiophysics from 1944; Chief of Division of Radiophysics from 1946 to 1971

Ewen, Harold Irving "Doc" (1921–2015) American; at Harvard University in 1951, he and Edward Purcell carried out the first detection of the Hydrogen line at 21 cm; later was President of the Ewen Knight Corporation and the Ewen Dae Corporation

Faraday, Michael (1791–1867) British; established the concept of the electromagnetic field and showed that magnetism could affect rays of light

Hanbury-Brown, Robert (1916–2002) British astronomer and physicist born in India, made notable contributions to the development of radar during WWII and the creation of intensity interferometers; University of Manchester and University of Sydney

Herschel, William (1738–1822) British astronomer born in Germany, discovered infrared radiation in sunlight

Hertz, Heinrich (1857–1894) German, physicist who proved the existence of electromagnetic waves and for whom the unit of frequency—cycles per second—is named

Hey, James Stanley (1909–2000) British physicist who detected radio emissions from sunspots while doing radar research during WWII; worked for the Army Operational Research Group and the Royal Radar Establishment at Malvern

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Hindman, J.V. (1919–1999) Australian radio astronomer who worked with Christiansen on the confirmation detection of the Hydrogen line and the initial H-line survey. He continued work on H-line surveys later at Parkes and then moved to the Australian National University, Siding Spring Observatory in 1967

Högbom, Jan (1929–) Swedish astronomer who developed the CLEAN algorithm for processing images made with radio telescopes; played a major role in the design of the Westerbork Synthesis Radio Telescope in the Netherlands

Hoyle, Fred (1915–2001) British astronomer known for his proposal (along with Gold and Bondi) of the Steady-State theory of the universe; major work was the theory of stellar nucleosynthesis; Cambridge University

Jansky, Karl Guthe (1905–1950) American physicist and engineer who first discovered radio waves arising from the Milky Way; Bell Labs

Labrum, Norm R. (1921–2011) Born in England and moved to Australia in 1946 taking a position in the CSIRO Division of Radiophysics. He worked in solar radio astronomy and together with Don McLean co-edited the book Solar Radiophysics [McLean, D.J., and Labrum, N. (eds.), 1985. Cambridge, Cambridge University Press]

Laby, Thomas Howell (1880–1946) Australian Professor of Natural Philosophy at the University of Melbourne

Little, Alec (1925–1985) Australian radio astronomer who worked with Ruby Payne-Scottt and Mills on instrument development and observations and later directed Molonglo Radio Observatory

Lovell, A.C. Bernard (1913–2012) British, Professor University of Manchester, Founder of the Jodrell Bank Observatory; during WWII, he was a prominent scientist in UK radar research, playing a major role in the development of the aircraft mounted H2S navigational system at 11 cm; the higher frequency version H2X could be used as a radar bombsite; after the war, the Jodrell Bank Observatory became a prominent research institution; the 250 foot telescope (now the Lovell Telescope) became operational in 1957; Lovell became a well-known public figure in the UK as a spokesman for science policy

Madsen, John P.V. (1879–1969) Australian, Professor of Electrical Engineering, University of Adelaide; founder of the Radio Research Board

Martyn, David Forbes (1906–1970) Scottish-Australian; leading CSIR (O) ionospheric scientist; first chief of CSIR's Radiophysics Laboratory

Maxwell, James Clerk (1831–1879) Scottish physicist; formulated the theory of electromagnetic radiation

McCready, Lindsay (1910–1976) Australian astronomer and engineer who specialised in receiver systems; worked with Ruby Payne-Scott in 1945–1951

Messel, Harry (1922–2015) Canadian-born Australian physicist and educator; Head of the School of Physics, University of Sydney

Minkowski, Rudolph (1895–1976) German-born American astronomer who studied supernovae and with Walter Baade made the first identification of the strong radio source Cygnus-A with a faint galaxy in 1954 using the 200 in telescope; Mount Wilson and Palomar Observatory in California

Minnett, Harry (1917–2003) Australian engineer who guided the design of the Parkes Radio Telescope; later Chief of CSIRO Division of Radiophysics, 1978–1981

Oort, Jan (1900–1992) Dutch astronomer; one of the discoverers of the rotation of the Milky Way in the late 1920s and in 1950 the “Oort Cloud” of distant comets in the solar system at distances of 100,000 times to the earth–sun distance; founder of radio astronomer in the Netherlands after WWII

O’Sullivan, John (1947–) Australian electrical engineer; Netherlands Foundation for Radio Astronomy, then CSIRO Division of Radiophysics; member of the group that invented Wi-Fi at CSIRO

Payne-Scott, Ruby (1912–1981) Australian, radar researcher at CSIR Division of Radiophysics during WWII; first woman radio astronomer, March 1944 observations made at 11 cm wavelength; discoverer of Type I and Type III solar bursts during the post-war rebirth of radio astronomy in Sydney; co-discoverer of Type II bursts (along with Yabsley and Bolton) in March 1947; left CSIRO in 1951 at the birth of her son, the prominent mathematician, Peter G. Hall (FRS 1951–2016)

Penzias, Arno (1933–) German-born American physicist, radio astronomer Nobel Prize in Physics 1978 with Robert W. Wilson for the discovery of the cosmic microwave background; Bell Labs

Purcell, E.M. (1912–1997) American physicist; along with Doc Ewen involved in detection of the 21 cm line of neutral hydrogen in 1951; Nobel Prize in Physics (1951) along with Felix Bloch for the discovery of nuclear magnetic resonance

Ratcliffe, John A. “Jack” (1906–1987) British radio physicist at the Cavendish Laboratory at the University of Cambridge UK; pioneering research on the ionosphere; during WWII prominent radar scientist at the Telecommunications Research Establishment in the UK; major role in the initiation of radio astronomy at Cambridge in the post-war years; thesis advisor of Pawsey and Bracewell

Reber, Grote (1911–2002) American electrical engineer; the second radio astronomer following Karl Jansky; he built his own 31 foot (9 m) radio telescope, conducting the first systematic radio sky survey; moved to Tasmania Australia in 1954 to work on low-frequency radio astronomy remaining until his death

Rivett, David (1885–1961) Australian chemist and science administrator, a major contributor to Australian science in the first half of the twentieth century; Chief Executive Officer of the newly formed CSIR (Council for Scientific and Industrial Research) from 1927 to 1946; played a major role in the formation of the Division of Radiophysics in 1939, as well as the administration of the radar research programme in WWII; from 1946 to 1949, he was Chairman of CSIR; retired in 1949 as the new Commonwealth Scientific and Industrial Research Organisation (CSIRO) was formed in May 1949

Ryle, Martin (1918–1984) British radio astronomer at Cambridge; for the development of radio astronomical aperture synthesis, he was awarded the Nobel Prize in Physics in 1974 (shared with Anthony Hewish); Ryle, Pawsey and Lovell were the first three radio astronomers to become Fellows of the Royal Society of London

Shain, C. Alex (1922–1960) Australian; low-frequency research at CSIRO at the field stations at the Hornsby and Fleurs

Slee, Bruce (1924–2016) Australian radio astronomer; important contributions to solar system, Galactic and extragalactic astronomy while working at CSIRO; he had detected the sun in late 1945 or early 1946 while a member of the Royal Australian Air Force using an aircraft warning radar antenna located near Darwin

Southworth, George C. (1890–1972) American engineer at Bell Labs known for developing radio frequency wave guides; he carried out the first high-frequency observations of the sun during WWII, published in 1945

Struve, Otto (1897–1963) Russian-born American astronomer; directed Yerkes Observatory of the University of Chicago at Williams Bay, Wisconsin; founding director of the McDonald Observatory near Fort Davis, Texas; served as the first director of the National Radio Astronomy Observatory from 1959 to 1962

Swarup, Govind (1929–) Indian radio astronomer; PhD at Stanford University with Bracewell in late 1960; founder of the radio astronomy group at the Tata Institute of Fundamental Research in Bombay; a leader in the design and implementation of the Giant Metrewave Radio Telescope

van de Hulst, Hendrik (1918–2000) Dutch astronomer; during the last year of WWII, he predicted the existence of the 21 cm hyperfine line of atomic hydrogen; leader in early radio astronomy in the Netherlands; major leader in the formation of astronomical research from space in Europe; University of Leiden

Warburton, J.A. (1924–2005) Australian; participated with Christiansen on construction and utilisation of the Solar Grating Array at Potts Hill before moving to work in Cloud Physics in 1957

White, Frederick William George (1905–1994) New Zealand-born ionospheric physicist who became the second Chief of the CSIR Division of Radiophysics in 1942, serving until 1944; then a member of the CSIR Executive; in 1949, he became the Chief Executive Officer; in 1959 when Sir Ian Clunies Ross (Chairman from 1949 to 1959) died, White became Chairman, serving until 1970

Wilson, Robert W. (1936–) American astronomer at Bell Labs and the Harvard-Smithsonian Center for Astrophysics; Nobel Prize in Physics in 1978 along with Arno Penzias for the discovery of the cosmic microwave background

Yabsley, Don E. (1923–2003) Astronomer with CSIRO; worked on radar during WWII; early solar research at Georges Heights, Sydney; he worked on the new Parkes Radio Telescope in the 1960s perfecting methods of determining the accurate shape of the antenna; later he played a major role in the design of the Australia Telescope in the 1980s

Zwicky, Fritz (1898–1974) Swiss-American astronomer; an iconoclast scientist who inferred the existence of dark matter based on observations of the velocity dispersion of individual objects in clusters of galaxies; based on his experience in observing supernovae with Walter Baade in the 1930s (the term “supernova” was coined by these two in 1934), Zwicky proposed that supernovae resulted from the transition of normal stars to neutron stars; he was a Caltech professor.

Appendix F: Abbreviations

AC	Companion of the Order of Australia
AST	Australian Synthesis Telescope
ASTRON	The Netherlands Institute for Radio Astronomy
AT	Australia Telescope
ATCA	Australia Telescope Compact Array
ATNF	Australia Telescope National Facility
AWA	Amalgamated Wireless (Australasia) Ltd
BOMAS	Bottom Mapping Sonar
CBE	Commander of the Most Excellent Order of the British Empire
CCIR	International Radio Consultative Committee
CMB	Cosmic Microwave Background
CMOS	Complementary Metal-Oxide-Semiconductor
CSIR	Council for Scientific and Industrial Research (Australia) 1926–1949 after which it became CSIRO
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
FFT	Fast Fourier Transform
FST	Fleurs Synthesis Telescope
GRT	Giant Radio Telescope—The working name for the Australian project that led to the 64 m Parkes Radio Telescope
IAU	International Astronomical Union
ICAO	International Civil Aviation Organization
ICSU	International Council for Science
IEEE	Institute of Electrical and Electronics Engineers
ILS	Instrument Landing System
K	Kelvin—the primary unit of temperature based on an absolute scale. The temperature increment is the same as Celsius. Absolute zero (O K) is −273.15 C
MGPS-2	Molonglo Galactic Plan Survey—No. 2
MOST	Molonglo Observatory Synthesis Telescope

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MSH	Abbreviation for the Mills, Slee and Hill survey that catalogued over 2000 discrete radio sources between 1954 and 1957
NRAO	National Radio Astronomy Observatory (USA)
NSF	National Science Foundation (USA)
OTC	Overseas Telecommunications Corporation (Australia)
PLANS	Program for Local Area Network Systems
PPI	Plan Position Indicator—a radar display of azimuth and range
RAAF	Royal Australian Air Force
RPL	Radiophysics Laboratory (CSIRO Australia)
SKA	Square Kilometre Array
SKAMP	Square Kilometre Array Molonglo Prototype
SNR	Supernova remnant
SUMSS	Sydney University Molonglo Sky Survey
TGV	TGV is France's intercity high-speed rail service (Train a Grande Vitesse)
URSI	Union Radio-Scientifique Internationale—International Union of Radio Science
VFT	Very Fast Train
VLSI	Very-Large-Scale Integration
VOR	Very-High-Frequency (VHF) Omnidirectional Range
WST	Westerbork Synthesis (radio) Telescope

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