History of Solar Magnetic Fields since George Ellery Hale

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Abstract As my own work on the Sun's magnetic field started exactly 50 years ago at Crimea in the USSR, I have been a participant in the field during nearly half the time span since Hale's discovery in 1908 of magnetic fields in sunspots. The present historical account is accompanied by photos from my personal slide collection, which show a number of the leading personalities who advanced the field in different areas: measurement techniques, from photographic to photoelectric and imaging methods in spectro-polarimetry; theoretical foundations of MHD and the origin of cosmic magnetic fields (birth of dynamo theory); the quest for increased angular resolution from national projects to international consortia (for instruments both on ground and in space); introduction of the Hanle effect in astrophysics and the Second Solar Spectrum as its playground; small-scale nature of the field, the fundamental resolution limit, and transcending it by resolution-independent diagnostics.

Keywords Sun: atmosphere · magnetic fields · polarization · dynamo · magnetohydrodynamics (MHD)

1 Sunspots as a window to cosmic magnetism

Astrophysics can be seen as remote sensing: the information on the physical conditions in the universe reaches us encoded in the spectra that we record with our telescopes. Our task is to decode that information through spectral analysis.

With the discovery by Pieter Zeeman (1897) of the Zeeman effect, it became known that magnetic fields leave their encoded "fingerprints" in the splitting and polarization of spectral lines. Through spectro-polarimetry we can therefore extract information on magnetic fields in remote objects. George Ellery Hale was the first to make use of this opportunity in astrophysics. He had noticed how the shape of the Sun's corona suggests that the Sun is a magnetized sphere with a global dipole-like field, and that the filamentary vortex structure of the H α fibrils around sunspots indicate that sunspots are the seats of strong magnetic fields and vertical electric currents. This led him to look for and find pronounced Zeeman splitting in sunspots (Hale 1908).

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Fig. 1 George Ellery Hale and his dicovery of magnetic fields in sunspots through observations of the Zeeman effect. At the place where the spectrograph slit crosses a sunspot the spectral lines get split in polarized components. The magnitude of the splitting is proportional to the magnetic field strength, while the polarization state (circular or linear) reveals the orientation of the field.

Sunspots thus became the gateway to the exploration of cosmic magnetic fields, including the origin of the fields and their role in astrophysical plasmas. We now know that magnetic fields govern most cosmic variability on intermediate time scales and pervade all cosmic plasmas, generating structuring, thermodynamic effects, and instabilities. Measurements of the Sun's magnetic field has guided the development of magnetohydrodynamics and dynamo theories.

The pioneering work by Hale and his team led to the discovery of Hale's polarity law (the law that governs the E-W orientation of the sunspot polarities with respect to solar hemisphere and 11-yr cycle), which showed that the magnetic cycle is 22 yr (the Hale cycle), twice the length of the sunspot cycle (Hale et al. 1919). Another fundamental discovery in the same paper is Joy's law, which tells that the polarity orientation of bipolar magnetic regions deviates systematically (in a statistical sense) from the E-W direction: the orientation is tilted so that the leading part of the region (with respect to the direction of solar rotation) is closer to the equator than the following part. Hale's and Joy's laws serve as observational cornerstones of solar dynamo theory. The Sun's dynamo can be seen as a prototype for all cosmic dynamos.

2 The enigmatic general magnetic field of the Sun

Soon after his discovery of magnetic fields in sunspots Hale wanted to explore the non-spot "background field", the so-called "general" magnetic field of the Sun, which he believed to be a global dipole based on the appearance of the solar corona at eclipses. The observational technique was to place a grid of mica strips across the spectrograph slit, so that one gets an alternating sequence of left- and right-handed circularly polarized spectra. In the presence of a magnetic field there would be a relative line displacement between the opposite polarization states.

The spectra were recorded on photographic plates, and the line positions were determined manually with a micrometer. With modern standards this was a crude technique not adequate for detection of the weak background fields. Aware of the marginal nature of this undertaking and the danger of subjectivity in the results, Hale let many of his assistants independently reduce the same plate material, and he claimed in the publications that the persons reducing the data were not informed about which heliographic latitude a given plate referred to. This was supposed to eliminate possible bias from the results.

2.1 An example of personal bias

All of the assistants except two got null results (consistent with what is to be expected in view of the measurement uncertainties). One of these two was a young postdoc who had recently arrived to Pasadena from Holland, Van Maanen. He immediately impressed Hale by getting positive results, and Hale gave most weight to his findings. This resulted in claims that the strength of the polar field was about an order of magnitude stronger than we find with modern, far more accurate techniques (Hale et al. 1918). In addition the polarity of the polar fields was opposite to what one would expect according the much later discovered model of the solar cycle by Babcock (1961).

In 1968, shortly after completion of my Doctoral Thesis with the title "The Sun's Magnetic Field", I spent seven months in Pasadena with the Mt Wilson Observatory and decided to use this opportunity to explore the Hale archives in search for an explanation of his enigmatic results on the Sun's general magnetic field. I was able to locate 400 photographic plates recorded in 1914, together with the meticulous notebook of Van Maanen with his micrometer measurements of the Zeeman shifts for each of these plates. After having the plates carefully cleaned I took them in my car and drove to the Sacramento Peak Observatory (Sunspot, New Mexico), where they had a digitized microphotometer with which I could (with the help of Jacques Beckers) have all the plates scanned. I then brought the big magnetic tapes with the scanned data to Lund, Sweden, where I analyzed them with a CDC mainframe computer. My computer reduction gave null results (within the standard error) for the general magnetic field, while Van Maanen had found for the same set of plates a field much stronger than the standard error, which varied with heliographic latitude as a global dipole field with the wrong polarity (Stenflo 1970).

Around the time of Hale's pioneering solar work the astronomical community was involved in an intense debate on the nature of spiral nebulae: Were they "island universes" (what we now call galaxies), or were they nearby objects inside our Milky Way system? Van Maanen joined this debate and provided what at that time seemed to be very convincing evidence against the island universe idea. Around 1922-1923 he measured on photographic plates substantial proper motions along the spiral arms of M33, which implied that the rotation period of M33 was smaller than that of the Milky Way by a factor of one thousand and that M33 could therefore not be very distant and large but had to be inside our galaxy (cf. Lundmark 1926). We now know that M33 is a galaxy and that whatever Van Maanen measured was not a real property.

2.2 The photoelectric magnetograph

The general, background magnetic fields, which we now refer to as quiet-sun magnetic fields, gave too weak Zeeman-effect signatures to be measurable with the technology that

was available to Hale. Further progress had to wait until the breakthrough in sensitivity provided by the photoelectric magnetograph, introduced by Babcock (1953). Instead of manually measuring wavelength positions of spectral lines on photographic plates one used photomultipliers as detectors and electro-optical polarization modulation with an ADP-type Pockels cell. Two exit windows in the spectral focal plane selected the light from the blue and red wing of a chosen Zeeman-sensitive spectral line. A servo-controlled tilting glass plate near the spectral focal plane kept the spectral line centered with respect to the two exit slits. The tilt angle of the plate represented the measured Doppler shift. The modulated polarization signals from the two line wings have opposite signs — today we say that the Stokes V profile is anti-symmetric) and then demodulated.

Since photomultipliers are "1-pixel detectors", a circular-polarization image (which represents a "magnetogram") could only be built up through raster scanning of the solar image. The initial observations were crude, with a spatial resolution of order one arcmin, but they allowed the recording of full-disk magnetograms with a polarimetric sensitivity that was sufficient for mapping the weak background fields. Thus Babcock could initiate a synoptic full-disk magnetogram program at the Mt Wilson Observatory.

This synoptic program led Babcock to the discovery that the general magnetic field, in particular the field in the polar caps of the Sun, reverses sign every 11 years. Thus not only the sunspot polarities but also the global magnetic field varies with the 22-yr Hale cycle. The photoelectric magnetograph gave us a comprehensive empirical picture of solar magnetism. The underlying mechanism that governs the Hale cycle must physically link the behavior of sunspots with the behavior of the global field.

Babcock (1961) could integrate the various empirical results into a phenomenological theory for the solar cycle, which explicitly clarified how the bits and pieces were connected. The Hale cycle represents an oscillation between a poloidal and a toroidal configuration of the magnetic field. The frozen-in field lines of the poloidal field are wound up by the latitudinal shear of the Sun's differential rotation, so that a toroidal field is built up. When the strength of the amplified toroidal field exceeds a certain theshold, magnetic tension can no longer prevent buoyant sections of the subsurface flux ropes to float up to the surface to form bipolar magnetic regions with polarity orientations in the general E-W direction, with opposite orientations in the N and S hemispheres, as required by Hale's polarity law. During the rise to the surface the flux loop is rotated by the Coriolis force, resulting in a systematic tilt of the bipolar orientation with respect to the E-W direction, in qualitative agreement with Joy's law. The tilt is such that the poleward (following) part of the bipolar region has a polarity that is opposite to that of the polar fields in the same hemisphere. When bipolar regions age, they fragment and spread by turbulent diffusion to form the general background field. Because of the initial tilt of the bipolar regions it is the following polarity that will dominate the new background field at high latitudes, thereby cancelling and reversing the polar field. Coriolis forces acting on buoyant toroidal flux combined with turbulent diffusion thus lead to a regeneration of a poloidal field with reversed polarity.

While Babcock's model was phenomenological, qualitative, and descriptive, it contained the physical ingredients that are central to modern dynamo theories. Leighton (1969) significantly extended Babcock's model by giving it a formulation in terms of a set of semi-empirical equations that could be used for quantitative modeling of the evolution of the pattern of surface magnetic fields. The Babcock-Leighton framework has been used since the early 1980s by Neil Sheeley and coworkers at NRL (e.g. Sheeley et al. 1985) for systematic modeling of the field pattern to understand its role for coronal holes, solar wind streams, and other large-scale phenomena on the Sun.



Fig. 2 The principles of the Leighton photographic magnetograph are illustrated to the left, from Leighton (1959). With a polarizing beam splitter two images in opposite circular polarization states of the chosen solar region are formed at the entrance slit of the spectrograph. The photographic plate is located behind the exit slit in the spectral focus. The entrance and exit slits are scanned in unison to build up monochromatic images (spectroheliograms) on the photographic plate. After the plate has been developed, the two orthogonal-polarization images are subtracted, to give a magnetogram like the one in the right part of the figure (from Vrabec 1971). It reveals the network structure of the magnetic-field pattern.

2.3 The magnetic network

With the superior sensitivity of the photoelectric magnetograph one might think that the days of doing magnetometry with photographic plates were over. However, photographic plates represented 2-D detectors with an enormous number of "pixels", which for mapping purposes with high angular resolution represented a huge advantage over photomultipliers, which are 1-pixel devices.

Robert Leighton developed a photographic magnetograph technique based on the photographic recording of two simultaneous spectroheliograms in orthogonal circular polarization states (Leighton 1959), as illustrated in the left portion of Fig. 2. Subsequent photographic subtraction of the two images then results in a polarization map (line-of-sight magnetogram). Such photographic subtraction is of course a tricky business due to the non-linear response of photographic plates, but Leighton and his followers developed it into an art.

One place in particular where the Leighton technique was perfected to produce not only high-resolution maps but also magnetic-field movies of outstanding quality was the San Fernando Observatory. The right part of Fig. 2 gives an example, from Vrabec (1971), of such a magnetogram, which clearly reveals that the magnetic pattern has a network structure. Remarkable movies of the moat structure around sunspots were made, showing how flux fragments of opposite polarities stream away from the spots.



Fig. 3 Neil Sheeley in his Tucson office in 1968. He perfected the art of recording Kitt Peak spectroheliograms to explore the photospheric network.

Leighton also used his subtractive spectroheliogram technique to make full-disk Doppler maps of the Sun, which led to his discovery of the supergranulation (Leighton et al. 1962). The largely horizontal flows in the supergranulation were much more effective than the granular flows for the redistribution of the fields through "turbulent diffusion". They came to play a major role in Leighton's kinematic model of the solar cycle, in which he treated the redistribution as a random walk on the solar surface of the frozen-in field lines.

Spectroheliograms had since many decades been an established tool to make narrowband monochromatic images of the Sun for any chosen wavelength in the visible solar spectrum. They had revealed that chromospheric lines like the H and K lines of ionized calcium show a network-like emission pattern. Leighton's Doppler and magnetic-field maps showed that both the supergranular velocity network and the magnetic-field network were closely correlated with the emission network, they seemed to coincide with each other. The statistical correlations between these three types of network were intensely explored by many solar physicists around the end of the 1960s, in particular by recoding Doppler and magnetic data through raster scans with a photoelectric magnetograph, which generally allowed the analysis to be more quantitative than with the photographic method.

In 1967 Neil Sheeley published a seminal paper in which he showed that many photospheric lines had line gaps (very significant line weakenings) at the locations of the quiet-sun network, and that these were places with strong, small-scale flux concentrations, with field strengths reaching up to hundreds of G (Sheeley 1967). In spectroheliograms the line gaps show up as a photospheric emission network. Subsequently Chapman and Sheeley (1968) made an extensive spectroheliogram survey of the behavior of different photospheric spectral lines with various excitation potentials, to demonstrate that the line gaps were the result of increased photospheric temperature. The observations allowed the temperature structure of the photospheric network to be modeled.

Sheeley's hundred G quiet-sun field strengths were shockingly high for that time, but they still represented a lower limit determined by the spatial resolution of his instrument.



Fig. 4 Examples of maps of vector magnetic fields in regions around sunspots, from Severny (1966). The top panel shows how the field azimuth rotates as observed with four spectral lines formed at different heights. The contours represent the sunspot umbra and penumbra. In the bottom panel the thin solid contours represent the longitudinal magnetic field, superposed on the background of short lines that represent the strength and orientation of the transverse magnetic field.

Since the intrinsic sizes of the network elements were not known and therefore not their filling factors f, the intrinsic field strength would be 1/f times the apparent field strength.

To find the intrinsic field strength without achieving infinite angular resolution one had to come up with a resolution-independent approach, which occurred soon afterwards with the introduction of the magnetic line-ratio method (cf. Sect. 5.2).

3 Mapping the vector magnetic fields and electric currents

Already Hale in his early work on sunspot magnetic fields knew how to combine the measured circular and linear polarizations of the longitudinal and transverse Zeeman effects to derive the magnetic-field vector (strength and orientation of the field). Formally such a Zeeman-effect "inversion" is very straightforward. In practice the inversion often leads to false results because of a combination of factors, in particular non-linear response, non-Gaussian noise, and unknown subresolution structure of the field. In contrast to the transverse Zeeman effect, the polarization of the longitudinal Zeeman effect has a nearly linear dependence on the field (via its line-of-sight component) with a Gaussian noise distribution, and also has high field sensitivity. This is the reason why most observational explorations of the magnetic field has been of its line-of-sight component. What we call "magnetogram" is always a circular-polarization map; in the more rare cases when also the Zeeman effect in the linear polarization is being recorded we use the term "vector magnetogram".

Soon after Babcock's introduction of the photoelectric magnetograph his concept was being extended at various places, including Crimea, IZMIRAN (near Moscow), Pulkovo by Leningrad, and Ondřejov by Prague, to record vector magnetic fields. Both the circular and linear polarizations in a selected spectral line were modulated by Pockels cells. The demodulated signals were recorded with ink pen on strip-chart recorders and combined to give the magnetic-field vector. The pioneering work in vector magnetometry was done at the Crimean Astrophysical Observatory, where Stepanov and Severny (1962) published the



Fig. 5 Dimitry Nikolaevich Rachkovsky (1928-2013), who gave us a comprehensive formulation of LTE radiative transfer of the full Stokes vector in magnetized media, including magneto-optical effects. His formulation is used in all current Stokes inversion work. The photo was taken in 1989 in Kiev.

first vector-field maps of the Sun. Figure 4 from Severny (1966) shows an example of maps of the vector magnetic field around sunspots (see also Severny 1964).

Vector magnetometry was a hot topic in solar physics of the 1960s, because it was seen as a tool for the exploration of the full MHD structure of the solar atmosphere. Maxwell's equations were being used to derive maps of the vertical electric current density from the horizontal gradients of the observed transverse magnetic fields. The pattern of vertical electric currents was found to correlate with the locations where flares occurred, as expected in the current-interruption theory of solar flares by Alfvén and Carlqvist (1967). Around that time Alfvén was finding it more revealing to describe MHD environments in terms of the electric current structure instead of magnetic fields, since currents are responsible for the pinch effect and could cause instabilities with the development of double layers, in which the MHD approximations break down.

The upper panel of Fig. 4 indicates how the apparent transverse field rotates with height in the atmosphere. Superposing the results obtained with four spectral lines formed at different heights one reveals how the azimuth angle varies. This behavior suggests that the field lines are twisted, as expected in the presence of vertical electric currents. However, the interpretation has to also account for the apparent twist induced by magneto-optical effects.

The Crimean Astrophysical Observatory was not only the world-leading institute in vector magnetometry, it was also the place where the theoretical foundations for the interpretation of magnetograph measurements were developed. While Wasaburo Unno in Japan had published a phenomenological but correct derivation of the radiative transfer equation for the Stokes vector (Unno 1956), it was the work of Stepanov and Rachkovsky at Crimea that brought us a self-consistent mathematical derivation that also included the magneto-optical effects. While Stepanov formulated this approach (Stepanov 1958a,b), Rachkovsky completed the theory to give us a mathematically stringent and comprehensive (within the assumption of LTE) formulation of the Stokes vector radiative transfer problem (Rachkovsky 1962a,b). Rachkovsky's theory was used to identify observational signatures of magnetooptical effects in the recordings with the Crimean magnetograph.

In 1965 the academies of sciences in Sweden and the Soviet Union signed an exchange agreement. It happened, thanks to the contacts and support of my mentor Hannes Alfvén, that I was the first from the Swedish side to be sent over to work in the USSR under this agreement. Alfvén believed that the Sun's magnetic field had a filamentary fine structure induced by the pinch effect of electric currents, and that this fine structure invalidated Babcock's observations since it was not resolved. He conjectured that if the field consisted of



Fig. 6 At the Crimean Astrophysical Observatory in 1965: Jan Stenflo and the observatory director, Andrei Borisovich Severny, the leading Soviet solar physicist at the time.

"microspots" with less visibility because of their different thermodynamic properties, then the spatial averaging process would lead to the wrong interpretation of the measurements (Alfvén 1967).

Alfvén had a strong incentive to see Babcock's results invalidated, since a general magnetic field that reversed sign every 11 years contradicted Alfvén's own theory of the solar cycle. He sent me to Crimea with the mission to confirm his conjecture by exploring the fine structure with the Crimean magnetograph. My mission failed, since my work rather helped to validate Babcock's results. However, Alfvén's ideas put me on a path to explore the nature of the unresolved magnetic fine structure and how it can be properly diagnosed. This path took me in productive directions that none of us could foresee at that time.

Thus at age 22 I spent three summer months in 1965 to study the fine structure of quietsun magnetic fields with the Crimean magnetograph, and I returned for another four months in the summer of 1966. This work gave the observational basis for my Doctoral Thesis, which I completed in the spring of 1968 (at the University of Lund, Sweden). Figure 6 shows me during the visit in 1965 together with the Director of the Crimean Astrophysical Observatory, Andrei Borisovich Severny, who was the most prominent Soviet solar physicist at the time.

The Crimean Astrophysical Observatory was a world leader in solar physics in the 1960s, it was an exciting time to be there. However, towards the end of the decade began a period of political and economic stagnation and decline, which finally ended in the collapse of the Soviet Union. Figure 7 contains photos that I took of the solar magnetograph when I visited Crimea again in 2011. The electronic equipment, control panels, and strip-chart recorders were much the same as when I worked there 45 years before. It was like going back in time, not much had changed. In the right panel is Valery Kotov, who still uses this equipment to study the 160-min oscillations of the Sun. I became befriended with him in 1965, when he was a PhD student at Crimea. In his thesis on the electromagnetic structure of active regions he used vector magnetic-field mapping not only to determine the vertical electric-current density, but also the horizontal current density and therefore the *vector electric currents*. The horizontal electric currents were found by recording the transverse



Fig. 7 Control panels and strip-chart recorders of the Crimean magnetograph system in photos taken in 2011. The equipment has not changed much since the mid 1960s. In the right panel is Valery Kotov, who used the instrumentation in the 1960s to determine the vector electric current structure of active regions, and who is now using it for continued studies of the Sun's 160-min oscillations.

magnetic field at different heights, and then from the height gradients of the horizontal field components use Maxwell's equations to obtain the horizontal components of the current.

Since there has been a revival in the mapping of vector magnetic fields in recent years in the context of Stokes inversions, one may wonder how reliable all the pioneering results from the 1960s about the vector magnetic fields were. My general answer is that the maps of the relative distributions of azimuth orientations of the transverse fields are reliable (as long as one accounts for the magneto-optical effects in the interpretation). Likewise the maps of the line-of-sight flux density (regular magnetograms) are also reliable. However, the magnitudes of the transverse flux density have been greatly overestimated, with the result that the determined field inclinations are much too large, the fields appear much more transverse than they really are.

The main source of the problem is that the relation between the measured linear polarization and the transverse field strength is highly non-linear (in contrast to the case for the circular polarization). This has two consequences for observations that do not have high S/N ratio: (1) The spatial averaging over unresolved subpixel structures depends on the nature of this structuring. Ignoring this problem always leads to errors in the direction of artificially enhancing the transverse fields. (2) The noise distribution of the transverse fields is highly non-gaussian, with an extended non-gaussian tail that makes the fields look much more transverse than they are. Since in addition the polarization amplitudes that are produced by a given field strength are much smaller (by typically a factor of 25) for the linear polarization relative to the circular polarization, the noise infiltrates the transverse fields much more



Fig. 8 Jan Stenflo with his mentor Hannes Alfvén on the Pacific beach in La Jolla in 1968. Two years later Alfvén received the Nobel Prize in Physics for his discovery of what we now refer to as Alfvén waves.

than the longitudinal fields, always in the direction of making the fields appear much too transverse.

This problem does not go away by using improved Stokes inversion techniques, because it is not a technical problem. The only known way to fully eliminate the transverse-field bias (in the weak-field quiet-sun case) is to use a statistical approach with ensemble averages (cf. Sect. 5.5), averaging the Stokes Q linear polarization as observed away from disk center (to break the symmetry), without trying to convert Q to transverse field strength, since such conversion is the source of the non-linearities and the non-gaussian noise. Because the ensemble averages are independent of the spatial resolution of the instrument (since Q is proportional to the number of photons received), and because the noise distribution in Q is Gaussian and thus symmetric, the ensemble averages of Stokes Q give unbiased results that neither favors horizontal nor vertical. Application of this technique has shown that quiet-sun magnetic fields are preferentially vertical (with respect to the isotropic angular distribution) in the low to middle photosphere (as observed in photospheric lines over most over the solar disk) but become preferentially horizontal in the upper photosphere (as observed close to the solar limb, cf. Stenflo 2013a).

4 Origin of the Sun's magnetic cycle

We have seen how Babcock integrated the various empirical findings into a phenomenological model of the solar cycle, which contained the main physical ingredients that govern the activity cycle of the Sun in terms of an interplay between turbulence and magnetic fields in a rotating magnetized plasma. We are now convinced that these ingredients are responsible for the generation of large-scale magnetic fields all over the universe, not only in stars and planets, but also on galactic scales. The Sun's 22-yr magnetic cycle is a prototype for all cosmic dynamos.



Fig. 9 T.G. Cowling from Leeds, UK, in conversation with R.F. Howard from Mt Wilson Observatory, Pasadena, during the First Solar Wind Conference at Asilomar, California, in 1971. Cowling is best known for his anti-dynamo theorem (Cowling 1933). Bob Howard took over and modernized Babcock's work on recording full-disk solar magnetograms and developed the successful synoptic program of Mt Wilson magnetograms that has for many decades provided fundamental data on the global evolution of the magnetic field.

4.1 An incorrect theory worthy of a Nobel Prize

In a Letter to Nature in 1942 (my birth year) my mentor Hannes Alfvén presented (two decades before Babcock) an alternative explanation for the origin of the sunspot cycle (Alfvén 1942). In his scenario the Sun possessed a global dipole-like field that was a remnant from the formation of the solar system. This field therefore penetrated the core of the Sun, so it could not reverse (in contradiction to Babcock's later findings). At that time it was believed that the CNO cycle rather than the p-p reaction chain was responsible for the thermonuclear energy production. This had the consequence that the central temperature was considered to be as high as 25 million K, and that a steep temperature gradient would cause the solar core to be in a convective state. Alfvén therefore postulated that the sunspots originated from disturbances in the central regions of the Sun, and that these disturbances traveled as waves (later called Alfvén waves) along the global dipole field, emerging at the surface as sunspots.

We now know this explanation of the solar cycle to be incorrect. However, in this short paper Alfvén for the first time introduced the concept of MHD waves, explaining why disturbances in a magnetized plasma would propagate as transverse waves along the field lines with a speed that we now refer to as the Alfvén velocity. It was for the discovery of these waves that he received the 1970 Nobel Prize in Physcis. Although he introduced this wave concept within the context of an incorrect theory for the solar cycle, it was a Nobel-prize worthy discovery that has since played a fundamental role in all of plasma physics. It is an example of how wrong theories can contain elements of great value !

4.2 Beginnings of dynamo theory

The concept of explaining the origin of macroscopic magnetic fields in terms of dynamo processes goes back to Larmor (1919), but subsequent progress towards a viable theory was relatively slow. One serious obstacle was the "anti-dynamo theorem" of Cowling (1933) (cf. Fig. 9), which was a proof that an axially symmetric velocity field, like that of a rotating



Fig. 10 Eugene Parker (left), here at the 1968 COSPAR meeting in Tokyo, made seminal contributions in theoretical solar physics over a wide range of topics.

medium, was incapable of generating a dynamo. Such idealized geometries were insufficient, the symmetry had to be broken for dynamo action to occur.

While Walter Elsasser from the University of Utah had overcome this obstacle and established the mathematical framework of dynamo theory, and in particular applied it to explain terrestrial magnetism (Elsasser 1946, 1955), Eugene Parker of Chicago extended the ideas to the solar case and highlighted how Coriolis forces in a rotating and turbulent medium make the turbulence cyclonic and thereby can regenerate the poloidal field from the toroidal one (Parker 1955). Babcock made use of these ideas when he built his phenomenological model of the solar cycle. Parker was the leading theoretical solar physicist for several decades, with fundamental contributions over a broad range of topics, including the origin of the solar wind, the cause of intermittency in the photospheric magnetic flux, and the mechanism for coronal heating. Figure 10 shows him at the COSPAR meeting in Tokyo in 1968.

4.3 Mean-field MHD and the α - ω dynamo

Alfvén had heard that Max Steenbeck in Jena, DDR, had developed a new and comprehensive formulation of the dynamo problem, and therefore sent me to Jena in 1969 to find out how the theory worked. Max Steenbeck was a leading person in the East German establishment, head of the country's research council with the rank like that of a government minister. However, he was foremost an innovative scientist, who had built up a leading group in plasma physics in Jena. Soon after my arrival he took me into his office, called in his young collaborators Fritz Krause and Karl-Heinz Rädler, and described to me on the blackboard the ideas behind the $\alpha - \omega$ dynamo. Figure 11 shows Steenbeck at his desk on that occasion in 1969.



Fig. 11 Max Steenbeck in his office in Jena in 1969. He was the "father" of mean-field electrodynamics and $\alpha - \omega$ dynamo theory.

The key to a comprehensive mathematical formulation of the dynamo problem was the development of mean-field electrodynamics (Steenbeck and Krause 1969). Assuming that the spatial and temporal scales of the turbulence are small in comparison with the global scales to allow ensemble avergaging, one could express the statistical effect of cyclonic turbulence as an electromotive force along the field lines with α as the proportionality constant. A second-order term in the ensemble average of the turbulence represented turbulent diffusion with coefficient β . The poloidal field lines get wound up by the shear (radial and latitudinal) in the Sun's rotational angular velocity ω . The evolution of the global solar magnetic field can then be formulated in terms of two coupled equations describing the interplay between the α , β , and ω effects, one equation for the poloidal component, one for the toroidal. Decomposition of these components in their spherical harmonics leads to a coupled system of equations for the eigenvalue problem, which allows very explicit and consistent modeling of the solar cycle. This type of modeling is very general and can be applied to account for the magnetic fields in various types of other stars, planets, and galaxies.

I returned to Jena in 1970 at the time when the institute was being moved from Jena to Potsdam, and I participated in the move. The Potsdam institute established itself as a leading center for dynamo research during the following decades.

4.4 Synoptic programs

In the caption to Fig. 9 we mentioned how Bob Howard took over the pioneering work of Horace Babcock and developed the first synoptic program for full-disk line-of-sight component magnetograms recorded daily at the Mount Wilson Observatory. Later (in the early 1970s) similar synoptic programs were started at Stanford by John Wilcox and at Kitt Peak by Bill Livingston and Jack Harvey. The Stanford program continues to this day with well defined but low spatial resolution. The Kitt Peak program has had the highest spatial resolution of the ground-based programs and was upgraded in the late 1990s by Jack Harvey and Christoph Keller as part of the SOLIS synoptic program.

The most advanced synoptic full-disk magnetogram projects have been the space programs *SOHO*/MDI (1995-2011) and its superior successor, *SDO*/HMI. Both have been managed by the Stanford group.



Fig. 12 John Wilcox (left) with Jan Stenflo in 1967 at the Swedish solar station on Capri, Italy. Wilcox was a leading solar wind scientist and founded the synoptic full-disk magnetogram program at the Stanford University.

John Wilcox had close contacts with Hannes Alfvén and was in the audience in Stockholm when I in 1966 gave a colloquium at Alfvéns institute on my observations of the Sun's magnetic fine structure at the Crimean Astrophysical Observatory. His main scientific focus at the time was on the physical properties of the solar wind and its sources on the Sun. He visited me at the Swedish solar station on Capri in 1967 (see Fig. 12). When I for the first time set foot on US soil (in 1968 after the defense of my Doctoral dissertation in Lund) Wilcox had arranged that I spent the first four nights at the Faculty Club of the Berkeley campus (later Wilcox moved from Berkeley to Stanford). I had made a world-around trip, so I entered the US from the west. It was Berkeley June 1968 at the height of the Vietnam war, and it was my first impression of what American society was like !

After Wilcox' tragic accidental death in 1984 by drowning while swimming in Hawaii, the synoptic Stanford Solar Observatory was renamed Wilcox Solar Observatory.

5 The quest for angular resolution

When the Sun is observed with improved angular resolution we discover previously unknown structures which deepen our physical understanding, like the granular convection pattern, the chromospheric filamentary structures, network and internetwork bright points, etc. Photospheric magnetic flux is highly intermittent with basic kG flux elements having typical sizes of order 100 km or below. Most of the size distribution is beyond reach of current telescopes, although flux tubes in the larger-scale tail of the distribution have been resolved. The magnetic-field pattern has a fractal-like structure, with a structuring that continues far beyond the resolution limit.

It has therefore always been a high priority for solar physicists to push for ever higher angular resolution, since it is widely believed that the fundamental physical mechanisms to a large extent are connected to processes at the smallest scales.

5.1 JOSO and LEST

Half a century ago the leading solar physics facilities were in the US (Mount Wilson in California, Kitt Peak with the McMath telescope in Arizona, Sacramento Peak in New Mexico) and the USSR (Crimean Astrophysical Observatory). The European solar physics community felt a strong need to overcome the political fragmentation after two devastating world wars and create a joint European solar facility that would again give Europe a leading role in science, as had been done by CERN for particle physics and by ESO for night-time astronomy. The driving force behind this pan-European solar physics movement was Karl-Otto Kiepenheuer, Director of the Fraunhofer Institute (after his death renamed Kiepenheuer Institute for Solar Physics) in Freiburg, Germany. In the late 1960s Kiepenheuer set up an informal European organization with the name JOSO, Joint Organization for Solar Observations (Kiepenheuer 1973), which had the goal of constructing a major European solar telescope, LEST (Large European Solar Telescope). This goal was to be achieved in two steps: (1) Search by systematic site testing campaigns for the optimum location of LEST. (2) Establishment of a new organization with legal structure and adequate financial means to design and construct LEST at the chosen site.

Figure 13 shows Kiepenheuer at one of the first meetings of JOSO, in Freiburg 1969. Beside him is Jean Rösch, Director of the Pic du Midi Observatory, representing France. Holland was represented by Kees de Jager, who founded the journal Solar Physics and later served as president of COSPAR, Italy by Guglielmo Righini, Director of the Arcetri Observatory in Florence, while I was representing Sweden.

After having done site testing of a number of coastal sites in Portugal, Sicily, and Greece it was concluded that high-altitude volcanic island sites would be better, and that therefore the site testing should concentrate on Tenerife (Izaña) and La Palma (Roque de los Muchachos) in the Canary Islands. Towards the end of the 1970s these site testing campaigns came to the conclusion that both Izaña and Roque de los Muchachos were indeed outstanding sites of comparable quality. There was no clear recommendation which of the two was better. Both are at the same elevation, just above the well-defined inversion layer where the clouds form. At these sites the wind direction is most of the time such that the line of sight from the telescope to the Sun is in a laminar air flow if the telescope sits on top of a tower high enough to avoid ground turbulence. This leads to excellent seeing, while the high altitude causes scattered light from the sky to be low.

Rather than waiting for a LEST to be realized, various countries quickly decided to set up their national facilities on these sites. Germany chose Izaña, where the Kiepenheuer Institute in Freiburg built the VTT (Vacuum Tower Telescope) while the University Observatory of Göttingen set up the Gregory-Coudé telescope that they had transferred from their solar station in Locarno, Switzerland. Similarly the French built their THEMIS 90 cm aperture polarization-free telescope at Izaña. The Swedes (through their observatory director Arne Wyller, who had succeeded Yngve Öhman, founder of the Swedish Capri observatory) transferred their solar station in Anacapri to Roque de los Muchachos, where also the Dutch established themselves with the DOT (Dutch Open Telescope), designed by Rob Hammerschlag. Soon after, the telescope at the Swedish La Palma observatory was completely rebuilt with an innovative design by Göran Scharmer, who later took over as observatory director. Under Scharmer the La Palma facility became the unrivaled world leader in solar imaging with the highest angular resolution. No other solar facility in the world has yet consistently achieved such resolution.

In parallel with these national activities the efforts towards the realization of the LEST dream made rapid progress. A new organization, the LEST Foundation, was established in



Fig. 13 JOSO meeting 1969 in Freiburg, Germany. From left to right: Karl-Otto Kiepenheuer (Freiburg), Jean Rösch (Pic du Midi), Peter Brandt (Freiburg), Kees de Jager (Utrecht), Guglielmo Righini (Arcetri).

1983 with legal seat at the Royal Swedish Academy of Sciences. Its task was to execute the intentions of JOSO, to obtain the financial means, develop the detailed design, and to construct and operate LEST at the chosen site. The scientific aim was focused on recording magnetic fields with the highest possible spatial resolution (Stenflo 1985). Throughout its existence the LEST Foundation was led by a "triumvirate", with me as President, Oddbjørn Engvold of Oslo as Project Director, and Kai-Inge Hillerud of the Royal Swedish Academy in Stockholm as Executive Secretary. The innovative design was led by Engvold with crucial input from Richard Dunn, US master optical designer, who made the Sacramento Peak Observatory (New Mexico) become the leading high-resolution facility in the US, and from Torben Andersen, who was a Danish telescope designer at ESO. Since other non-European countries like the US and China joined the LEST Foundation as members, the acronym was redefined as Large Earth-based Solar Telescope, to emphasize that it was not just a European but a truly international undertaking.

Around the end of the 1980s the detailed design for the entire facility had been completed, the definite site had been selected (on Roque de los Muchachos near the Swedish La Palma observatory), we were ready to start the construction phase, and it appeared that the needed funding support was forthcoming (Engvold 1991). Dramatic external events changed the situation. When the Soviet Union collapsed, Germany turned all its priorities and financial resources toward the enormous task (and historical opportunity) of German reunification, with the consequence that the expected substantial German contributions to the construction phase of LEST would not be available in the foreseeable future. The LEST project was put on hold for another decade (although during this time many design studies for various focal-plane instrumentations were carried out), until it was finally decided to dissolve the LEST Foundation as of June 30, 2002.

As the LEST project lost momentum in the 1990s, the idea of a next-general type international solar facility was being developed in the US in the form of ATST (Advanced Technology Solar Telescope), with an innovative 4 m aperture telescope design by Jacques Beckers. This ambitious project, renamed DKIST (Daniel K. Inouye Solar Telescope) is now in construction at the Haleakala site on Maui and is expected to be in operation by 2020.

Before the LEST Foundation was dissolved, Torben Andersen and Oddbjørn Engvold designed a scaled down version of LEST, which has since been implemented in the form of the Chinese 1-m solar telescope at the Fuxian lake near Kunming and the 1.5-m German GREGOR telescope on Tenerife (which has replaced the 45 cm Göttingen Gregory-Coudé telescope). The original LEST idea of a joint European solar facility has been resurrected within Europe in the form of EST (European Solar Telescope), aiming for a telescope in the DKIST class, and it is progressing well with the help of EU funding.

5.2 The McMath-Pierce facility as a center of innovation

In the late 1960s and the following decades the leading US facility for solar observations with high spatial resolution was the tower telescope at the Sacramento Peak Observatory in New Mexico, which had been designed by Richard Dunn and later given the name DST (Dunn Solar Telescope). However, the main innovations and advances in the exploration of solar magnetic fields took place at the McMath telescope at Kitt Peak because of the many contributions of in particular William Livingston, Jack and Karen Harvey, Jim Brault, and Neil Sheeley. This giant telescope had been designed by Robert McMath but was renamed the McMath-Pierce facility after the death of the head of the Kitt Peak solar department, Keith Pierce.

Harvey and Livingston implemented innovative techniques for magnetic-field mapping, which much advanced our insight and understanding of the small-scale nature of the fields (cf. Livingston et al. 1976; Harvey 1977). Around 1974 they initiated the synoptic program of daily Kitt Peak full-disk magnetograms and synoptic maps that resolved the field in much greater detail than anywhere else. Jack's wife Karen discovered together with Sara Martin of the San Fernando Observatory the ephemeral active regions (Harvey and Martin 1973). Jim Brault developed a Fourier transform spectrometer (FTS) for the visible part of the spectrum (Brault 1978, 1985), which with the help of Jack Harvey could be converted into an FTS polarimeter.

My own main observational work has been done with the McMath-Pierce facility. In September 1971 I applied the magnetic line-ratio technique (with the 5250-5247 Å line pair) to discover that more than 90% of the magnetic flux that had been recorded in solar magnetograms (with a resolution of a few arcsec) on the quiet Sun actually is in kG form but appears weak since it is unresolved with a small filling factor (Stenflo 1973). In 1978-79 I used the FTS polarimeter to make atlases of the Stokes V spectra in plages and the network and surveys of the linearly polarized spectrum near the solar limb. The Stokes V spectra (Stenflo et al. 1984) led to detailed physical validation of the line-ratio technique, revealed the nature of the Stokes V asymmetries, and could be used by Sami Solanki, my first PhD student at ETH Zurich, to apply multi-line techniques for the empirical modeling of solar magnetic flux tubes. The linear polarization survey led to the discovery of the Second Solar Spectrum (cf. Sect. 6.2), which is formed exclusively by coherent scattering processes and is the playground for the Hanle effect. When the ZIMPOL technology had been developed



Fig. 14 Jack and Karen Harvey with Jan Stenflo at Stonehenge, 1970. Jack did ground-breaking work in the 1970s on the small-scale structure of solar magnetic fields, and Karen codiscovered the ephemeral active regions.

at ETH Zurich it was used from 1994 onwards at the McMath-Pierce facility for systematic explorations of the Second Solar Spectrum with a polarimetric precision of 10^{-5} . The main Hanle-effect constraints on the properties of the hidden turbulent magnetic fields have come from ZIMPOL observations at Kitt Peak.

The main reason why the McMath-Pierce facility has served as the premier place for innovative, experimental solar science is, besides its high light-gathering capacity (1.5 m entrance aperture) the large, open experimental environment in the spatious observing room, with free access to the large solar image and unrestricted access to the beam in front of the entrance slit of the spectrograph, which makes it simple to insert novel experimental equipment. Other large astronomical telescopes generally do not allow experimental freedom of this kind. It will be greatly missed with the closure of the McMath-Pierce facility.

5.3 FTS polarimetry

The FTS polarimeter allowed unprecedented insight into the physical nature of the spatially unresolved magnetic fields. It allowed the simultaneous recording of the spectra of Stokes I (the ordinary intensity) and one of Q, U, or V with full spectral resolution (absence of significant instrumental spectral smearing), no spectral stray light, and with simultaneous wavelength coverage over the full spectral range admitted by the broad-band prefilter used (typically 1000 Å). This was far beyond what one could dream of achieving with any spectrograph system. The trade-off was low angular resolution (5 arcsec at the time) and temporal resolution (tens of minutes). Since the vast majority of solar physicists had their focus on high spatial resolution, few took interest in the use of the FTS polarimeter, I became almost its only user.



Fig. 15 Illustration of a small spectral window from the Stokes *I* and *V* atlas of a weak plage, recorded with the FTS polarimeter in 1979 (Stenflo et al. 1984; Stenflo 2013b).

As an example Fig. 15 shows a 4.5 Å wide portion of the FTS spectral atlas of a weak plage recorded in 1979. In particular it illustrates the exact behavior of the Stokes V profiles of the lines Fe I 5247.06 and 5250.22 Å, which belong the magnetic line-ratio pair that was used with the McMath Babcock-type magnetograph system to reveal that most of the photospheric magnetic flux that had been recorded in magnetograms has its origin in strong, 1-2 kG bundled fields with small filling factors. Analysis of the observed Stokes V line shapes allows a detailed validation of this interpretation. The FTS Stokes V atlases are available both as pdf and data files at http://www.irsol.ch/data_archive/#ftsv .

The Stokes V spectral atlases and their center-to-limb variations represented a gold mine for the construction of empirical models of the spatially unresolved kG flux tubes, which was exploited by Sami Solanki in his PhD thesis project at ETH Zurich. Sami went on to become director at the Max-Panck-Institute for Solar System Research in Göttingen, where he led the successful *Sunrise* project to observe solar magnetic fields with unprecedented spatial resolution from a stratospheric balloon (Solanki et al. 2010).

The FTS polarimeter represented a remarkable advance in solar instrumentation, but it has now been decommissioned, and no similar instrument exists anywhere else. There are not even plans within any of the main solar telescope projects to build another instrument of this type. Like the 1970s represented a heroic era when we could fly people to the moon but are not able to do it any more (or have lost interest in it), FTS polarimetry represents a lost art, without sufficient motivation anywhere to resurrect it.

It is true that the FTS polarimeter in the 1970s had low spatial and temporal resolution and used 1-pixel detectors, but it was in principle possible to improve the resolutions and to use multi-pixel detector arrays, although it is technically difficult. However, these improvements were never done, because they were not requested by the broader solar community.

5.4 The endless debate on the existence of kG fields

Application of the magnetic 5250/5247 line ratio method through my 1971 Kitt Peak observations allowed me to conclude that most of the measured quiet-sun magnetic flux is in kG form (Stenflo 1973). For me the evidence was so clear that I considered the case as closed. Since however this conclusion was not reached by resolving the kG fields, but indirectly, through the identification of a telltale spectral signature that could not have any other interpretation, it took many years before my result found broad acceptance within the community, even after the interpretation got validated with the independent FTS polarimeter data. Over the years various people presented their own conclusions about the existence of quiet-sun kG fields as if it were a new discovery.

While as time went by ever fewer people questioned the existence of kG flux on the quiet Sun, two leading scientists within the solar community never accepted it: Andrei Severny, director of the largest astrophysical observatory in the Soviet Union, and Harold Zirin of Caltech, who founded the Big Bear Solar Observatory (which presently has the largest-aperture solar telescope in the world). After Severny passed away in 1987, Hal Zirin remained the stronghold of resistance.

Hal seemed to enjoy this controversy. In 1992 he organized an IAU Colloquium in Beijing and invited me to have a debate with him there on the reality of the kG fields (cf. Stenflo 1993; Zirin 1993). The debate between the two of us was set up to represent a highlight of the conference. The lively event did not change any opinions, but I remember the atmosphere as friendly and entertaining. Hal and I respected each other in spite of our opposite views.

Long after, it seems that some remember this event as a debate about whether the quietsun fields are weak or strong. This is not at all what it was about. There has always been agreement that most of the photospheric volume is filled with weak fields. The intermittent kG flux picture that resulted from application of the line-ratio technique implied that only about 1 % of the photospheric volume is occupied by kG fields, while the remaining 99 % has much weaker fields. The discovery of the kG fields was followed by a focus on finding the properties of the remaining 99 % weak fields. These efforts led to the discovery that one can use the symmetry properties of the Hanle effect to constrain the field strengths of these weak fields (Stenflo 1982).

So the Beijing debate in 1992 was not about whether the fields are strong or weak, it was whether there exist kG-type magnetic fields on the quiet Sun, which carry much of the magnetic flux that we see in solar magnetograms. Zirin always denied the existence of such fields, and he never gave up this position.

5.5 Ensemble averages and angular distributions

While the initial observations of quiet-sun magnetic fields by Babcock was with arcmin angular resolution, the observing techniques advanced rapidly in subsequent years, so that by the end of the 1960s an angular resolution of better than a few arcsec could be reached. With each new resolution breakthrough there was a tendency to proclaim that the magnetic structures had finally been resolved. We now know that such proclamations were wildly premature, since the magnetic structuring continues to far smaller scales (cf. Fig. 21 below).

With the realization that the fields remain largely unresolved came the need to find resolution-independent spectral signatures that could reveal the intrinsic properties of the fields as they would appear with infinite resolution. Since the field morphology is not resolved, such techniques must be statistical in nature, making use of ensemble averages of field elements to find the intrinsic statistical properties of the elements that make up the ensemble. The magnetic line-ratio method is an example of such a technique. Since the field elements are far from resolved, the angular-resolution window of the instrument averages over an ensemble of fields with a vast range of field strengths, both weak and strong. The *differential* effects between the ensemble-averaged Stokes V profiles of the 5250-5247 Å line pair allow us to conclude that most of the resolved Stokes V signal gets its contribution from intrinsically kG flux elements. The 5250-5247 pair is the only known line combination

for which the kG interpretation is unique, because thermodynamic and radiative-transfer effects are unable to produce differential effects of the observed kind (in contrast to the case for all other considered line combinations).

Two other types of spectral signatures from ensemble averages of Stokes parameters have led to profound insights into the hidden small-scale nature of solar magnetic fields: (1) Depolarization signature in the linear scattering polarization, caused by the Hanle effect of an ensemble of microturbulent (optically thin) magnetic fields with random orientations of their field vectors (Stenflo 1982). These fields represent most of the weaker (non-kG) fields that occupy approximately 99% of the photospheric volume. (2) Sign pattern of the ensemble-average of Stokes Q from the transverse Zeeman effect as observed away from disk center (which is needed to break the symmetry to give non-zero signatures). This sign pattern is an unbiased and resolution-independent signature of the vertical or horizontal preference (with respect to the isotropic case) of the angular distribution of the field vectors of the ensemble (Stenflo 1987, cf. the discussion at end of Section 3).

6 Hanle effect and the Second Solar Spectrum

Since Hale the Zeeman effect has been the main tool for the diagnostics of cosmic magnetic fields. In recent decades, however, the Hanle effect has emerged as a complementary tool that is sensitive to fields in parameter domains that are nearly inaccessible to the Zeeman effect. The main reason why it has not yet been so widely used but rather been an area for a smaller community of specialists is that the underlying physics is complicated and the applications are not so straightforward. The observations require higher polarimetric sensitivity, and the interpretations generally need vector radiative transfer with scattering and partial frequency redistribution in magnetized media, a subject area that is still not fully developed. The interpretations are also sensitive to the assumptions concerning the 3-D geometry of the atmosphere. Due to such complications much of the astrophysical exploitation of the Hanle effect still lies in the future.

The Hanle effect was discovered by Wilhelm Hanle (cf. Fig. 16) in 1923 during his PhD work in Göttingen (Hanle 1924). It played an important role in the early development of quantum mechanics because it represented an explicit expression of the concept of linear superposition of quantum states and the decoherence that is caused by an external magnetic field. It soon found applications over a wide range of fields in physics before it was realized that it could also have important applications in astrophysics (cf. Moruzzi and Strumia 1991). Hanle himself was enthusiastic when he learnt about the astrophysical applications.

6.1 Coherent scattering and Hanle effect on the Sun

The blue sky is polarized due to Rayleigh scattering at molecules in the Earth's atmosphere. Similarly the Sun's spectrum gets linearly polarized because coherent scattering processes in the continuum and the various spectral lines contribute to the formation of the spectrum. Magnetic fields are not the source of the scattering polarization, but they modify it and thereby generate observable spectral signatures. It is this magnetically-induced modification that is referred to when we speak of the Hanle effect.

It was realized already in the 1920s by Öhman (1929) that such scattering polarization should exist on the Sun. Yngve Öhman was the founder of the Swedish solar station on Capri and was one of my mentors (since I started my solar work on Capri at age 20 in 1963). The



Fig. 16 Wilhelm Hanle visiting me in my ETH office in 1983 on the occasion of the 60th anniversary of his effect.

first reliable observational evidence came when Günter Brückner recorded the scattering polarization near the Sun's limb in the Ca I 4227 Å line with the telescope at Göttingen's solar station in Locarno, Switzerland (Brückner 1963). In the mid 1980s the ownership of the observatory was transferred to Switzerland and it was renamed IRSOL (Istituto Ricerche Solari Locarno). Its scientific focus is the exploration of the scattering polarization and the Hanle effect with the powerful imaging polarimetry system ZIMPOL that was developed at ETH Zurich (see Sect. 6.2).

The first consistent interpretation of the non-magnetic 4227 Å observations in terms of polarized radiative transfer was made by Dumont et al. (1973) in Paris. The first observation of the Hanle effect in an astrophysical context was done in solar prominences by Leroy et al. (1977) at the Pic du Midi Observatory. Figure 17 shows Jean-Louis Leroy when I visited him at Pic du Midi in 1970.

The personal contacts developed during my extended periods of work in the Soviet Union in the 1960s led to the opportunity for Sweden to build instruments to be flown on Soviet Intercosmos satellites. Due to the severe limitations in space, weight, and telemetry we had to come up with an idea of doing something qualitatively different, not attempted with the much larger resources available elsewhere. Our choice was to build a Swedish spectro-polarimeter for the solar vacuum ultraviolet, to search for signatures of polarization due to coherent scattering in H Lyman α and in emission lines formed in the chromosphere-corona transition region. This project represented my own entry into the field of scattering polarization physics.

During the first attempt to launch the Swedish experiment, in 1975, the Soviet rocket exploded and all the experiments were destroyed. However, we had a spare model that could be successfully put in orbit the following year on the satellite Intercosmos 16 (the satellite that exploded was never assigned a number in the Intercosmos series — officially it did not exist). I participated in the launch preparations during three weeks at the super-secret military launch site of Kapustin Yar near Volgograd. It was the first time that anyone from a western country was admitted to a Soviet launch site.

Our UV spectro-polarimeter functioned as it was supposed to, but contamination of the UV optics due to outgassing in orbit from other parts of the spacecraft (because the integration had not been performed in a cleanroom but in a dirty garage environment) caused



Fig. 17 Jean-Louis Leroy (right) at Pic du Midi, 1970.

the optical transmission to quickly degrade by a factor of one hundred, increasing the polarimetric noise by an order of magnitude. It was therefore only possible to set an upper limit of 1 % for the H Lyman α scattering polarization near the limb as observed with one arcmin spatial resolution (Stenflo et al. 1980). Although this meager scientific output was a disappointment, the experiment demonstrated the feasibility of doing spectro-polarimetry in the vacuum ultraviolet.

There is considerable potential for using the scattering polarization and its magnetic modification via the Hanle effect in this part of the spectrum as a tool to explore the elusive magnetic fields in the chromosphere-corona transition region, where the physical processes responsible for coronal heating take place. Still, four decades later, this potential has not yet been exploited, but finally there is hope for some progress: the *CLASP* rocket experiment for recording the Hanle effect in H Lyman α is ready to be launched (cf. Ishikawa et al. 2011).

6.2 Second Solar Spectrum

The UV space experiment led to my interest in a systematic exploration of the physics of scattering polarization and its signatures in the Sun's spectrum. In 1978 I used the grating spectrograph and the FTS at the Kitt Peak McMath telescope to make a spectral survey of the linear polarization inside the solar limb, from 3165 to 9950 Å (Stenflo et al. 1983a,b). This led to the discovery of the so-called Second Solar Spectrum, which is the linearly polarized spectrum that is exclusively caused by coherent scattering processes on the Sun. For more convenience it is now referred to with the acronym SS2, implying that the ordinary intensity spectrum is SS1.

There is a need to refer to SS2 as a totally different spectrum because the fractional linear polarization Stokes Q/I is as richly spectrally structured as the ordinary intensity spectrum, but with structures that look entirely different and which are formed by largely different physical processes. Its discovery led to intense theoretical work trying to identify all the unfamiliar spectral features and develop the quantum-mechanical foundations for their interpretations. SS2 is a playground for the Hanle effect, but the underlying physics is complex and still not fully understood. A modern atlas of SS2 has been produced by



Fig. 18 Examples of various structures in the Second Solar Spectrum (SS2). The panels to the upper left show a nearly 200 Å wide portion around the strong Ca II K and H resonance lines (marked by the vertical dashed lines). The upper panel shows the intensity spectrum (SS1), the panel below SS2 with its remarkable polarization sign reversal, which has its explanation in terms of quantum interference between the K and H line scattering amplitudes, as indicated to the upper right. With the imaging polarimeter ZIMPOL it became possible in the late 1990s to zoom in on small sections of the spectrum, to uncover the enormous wealth of new kinds of structures in SS2, as indicated in the sets of panels in the lower half of the figure.

Gandorfer (2000, 2002, 2005) and is now available both in pdf and data format at http://www.irsol.ch/data_archive/#ss2.

Figure 18 gives an example of SS2 around the K and H lines of ionized calcium, to indicate the nature of some of the phenomena that we encounter in SS2. The nearly 200 Å wide section shown in the double panel to the upper left was recorded in 1978 (Stenflo 1980). The upper panel shows SS1 (the intensity spectrum) with the two dominating Ca II resonance lines, whose extended damping wings form a quasi-continuum that is populated by a multitude of blend lines. The strange shape of the SS2 spectrum in the panel below is a signature of quantum-mechanical interference between the J = 1/2 and 3/2 upper states of the H and K lines (Stenflo 1980), as indicated in the diagram to the upper right. The intermediate state of the coherent scattering process represents a "Schrödinger cat state", a coherent superposition of states having different total angular momenta. The resulting quantum interference is responsible for the sign reversal of SS2 in Fig. 18.

Although major SS2 features like those of the H and K lines in the upper part of Fig. 18 could be uncovered with the Kitt Peak observations in 1978, the polarimetric precision that could be achieved was not much better than 0.1 %, far insufficient for most of the SS2. It was only with the introduction of the ZIMPOL (Zurich Imaging Polarimeter) technology in the mid 1990s that the full wealth of spectral structures in SS2 became accessible to exploration. With ZIMPOL at Kitt Peak we could routinely reach a polarimetric precision better than 10^{-5} in combination with high spectral resolution. The lower half of Fig. 18



Fig. 19 Hanspeter Povel, who at ETH Zurich invented the ZIMPOL technology for CCD-based imaging polarimetry with a precision of better than 10^{-5} in the fractional polarization.

illustrates how this allowed us to zoom in on any small spectral section to expose the new world of polarization phenomena.

The ZIMPOL technology, which was invented by Hanspeter Povel at ETH Zurich (Povel 1995, 2001), revolutionized imaging polarimetry by achieving a polarimetric precision nearly two orders of magnitude better than other imaging systems. This opened a window to polarization physics that had not been accessible before. The problem had been that the available 2-D electronic detectors of CCD type have slow readout, which seemed incompatible with the fast (kHz) polarization modulation needed to eliminate seeing noise. If instead of modulation one would form the difference between two simultaneous images in orthogonal polarization states, the accuracy would be limited by gain-table noise, which is caused by inaccuracies in the flat-field calibration. Povel's solution to eliminate these two dominating noise sources was a way to create hidden fast buffer storage areas within the CCD sensor, between which the photocharges could be cycled in synchrony with the kHz polarization modulation. The second and later generations of the ZIMPOL system have four sets of fast hidden buffers, implying that the photocharges can be cycled between four simultaneous image planes within a single CCD sensor. Linear combinations between these four images give us the simultaneous images of the four Stokes parameters, free from seeing and gain table noise. The technology has now been successfully used in solar research for two decades.

The interpretation of the wealth of new phenomena in SS2 and the application of the Hanle effect for the diagnostics of solar magnetic fields require that the fundamental quantum processes that govern the interaction between matter and radiation in magnetized media are sufficiently understood. Figure 20 shows two of the main pioneers in the work to establish a foundation based on general principles in quantum field theory: Egidio Landi Degl'Innocenti of Firenze, Italy, and Veronique Bommier of Paris. They developed the theory in terms of the density matrix formalism with irreducible tensors, treated optical pumping by solving the statistical equilibrium problem for multi-level systems with atomic polarization, and applied the theory for the diagnostics of prominence magnetic fields (cf. Bommier 1980; Landi Degl'Innocenti 1983). The monograph by Landi Degl'Innocenti and Landolfi (2004) provides a comprehensive account of this theory.

An alternative approach to the scattering theory in terms of the Kramers-Heisenberg scattering amplitudes is presented in the monograph on solar magnetic fields by Stenflo (1994). It is particularly suited for the inclusion of the important effects of partial frequency redistribution effects in polarized radiative transfer with scattering in magnetized media. It has been the approach used by the groups in Bangalore (headed by K.N. Nagendra) and



Fig. 20 Egidio Landi Degl'Innocenti of Firenze and Veronique Bommier of Paris in 2013 during Solar Polarization Workshop No. 7 in Kunming, China. They helped establish the quantummechanical foundation for the interaction between radiation and matter in magnetized media.

Nice (led by Marianne Faurobert and Helène Frisch), who have developed the theoretical tools needed to interpret the SS2.

The physics of polarized radiation with the Zeeman and Hanle effects in magnetized stellar atmospheres has been the subject of a series of Solar Polarization Workshops that have taken place every three years in different parts of the world since 1995. The first of them was organized in St. Petersburg, Russia, by V.V. Ivanov, who coined the expression "Second Solar Spectrum", when referring to the linearly polarized solar spectrum that is formed by coherent scattering processes. The proceedings of these Workshops provide an updated account of the field. The latest is from Solar Polarization 7, which was held in Kunming in 2013 (Nagendra et al. 2014)

6.3 Scale spectrum of magnetic structures: empirical view

The ongoing quest to diagnose the smallest scales has led to the understanding that the magnetic structuring continues on scales orders of magnitude smaller than the resolved ones, down to the magnetic diffusion limit (of order 25 m), where the ohmic diffusion time scale becomes smaller than the convective time scale and the field lines therefore cease to be frozen-in and decouple from the plasma. Since most scales are still unresolved, indirect methods based on the observations of ensemble averages (see Sect. 5.5) have had to be used, with guidance from numerical simulations of magneto-convection, which have become increasingly advanced with the rapid growth in computing power.

Figure 21 gives a global overview of the empirically determined magnetic energy spectrum of the quiet Sun over seven orders of magnitude in scale size, from Stenflo (2014). The portion to the left of the vertical dotted line marked "Hinode resolution" (at a scale of about 200 km) is based on resolved observations with *Hinode* SOT/SP. The spectral bump immediately to the right of this line, at scales 10-100 km, follows from diagnostics with the line-ratio method, from which a population of intermittent kG flux elements with sizes in this range can be inferred. Theoretically the existence of such a flux population can be understood in terms of the convective collapse mechanism (Parker 1978; Spruit and Zweibel 1979).

One of the main applications of the Hanle effect has been to diagnose the properties of magnetic flux which is hidden to the Zeeman effect, because the magnetic elements are



Fig. 21 Empirically determined magnetic energy spectrum extending over seven orders of magnitude in scale (red line), from the global scales to the magnetic diffusion limit, where the field lines decouple from the plasma. The spectrum needs to be elevated in the optically thin inertial range to a power law of -1.0 to be compatible with the constraints from the observed Hanle depolarization effect. From Stenflo (2014).

optically thin with random orientations of their field vectors. When this method was first introduced (Stenflo 1982) it revealed the existence of a seething ocean of microturbulent magnetic flux with field strengths in the range 10-100 G. The most detailed radiative-transfer modelling of this Hanle depolarization effect with the use of 3-D atmospheres produced by MHD numerical simulations has led to a turbulent field strength of 60 G if a single-valued field is assumed (δ function PDF). With a more realistic PDF an average field strength about twice as large is obtained (Trujillo Bueno et al. 2004). The 60 G value should therefore be considered as a lower limit.

So much volume-filling flux in the optically thin scale range is not compatible with the standard Kolmogorov-type -5/3 power law (dashed line at high wave numbers in Fig. 21). The energy spectrum needs to be substantially elevated and flatter to be compatible with the Hanle observational constraints, which are best satisfied with the -1.0 power law that is illustrated in Fig. 21. Such an elevated spectrum cannot be explained in terms of the ordinary turbulent cascade from larger to smaller scales, there is a need for a new source of flux at small scales. This source could be provided by a local dynamo. While observations at resolved scales rule out a significant contribution from a local dynamo (Stenflo 2012), such dynamo action appears to be needed for consistency with the Hanle constraints.

7 Concluding remarks

Current research on solar magnetic fields is very diverse, with an interplay between theory (e.g. plasma physics, quantum field theory, polarized radiative transfer), observations (ground-based or space-based, polarimetric imaging with spectrographs or narrow-band filter systems, etc.), technological developments (detector and modulation systems, telescope technology, enhanced resolutions, computing power), and numerical simulations of magneto-convection. The present rather sketchy and personal overview has focused on some highlights that have advanced our empirical view of solar magnetic fields since the time of Hale. It is unavoidable that many of the important contributions to the field have not been covered here, because it is far beyond the scope of the present overview to aim for a comprehensive historical account.

Hale opened a new window to the universe by applying the physical effect discovered by Pieter Zeeman a decade before (Zeeman 1897). A new polarimetric window has now

been opened, although with much delay, by applying the physical effect discovered by Wilhelm Hanle at the time when quantum mechanics was being formulated in Göttingen (Hanle 1924). The complexity of all the coherence phenomena has led to a return to an exploration of the fundamental quantum nature of matter-radiation interactions in magnetized media. This work is still ongoing.

In contrast the non-coherent Zeeman-effect physics is well understood. The problems when applying it to the Sun arise because we sample an inhomogeneous medium in which the physical parameters vary over regions that are not resolved. Even if we could observe with infinite angular resolution, the spatial sampling along the line of sight remains about 100 km, since this is the typical depth of line formation. This is more than three orders of magnitude larger than the small-scale end of the magnetic energy spectrum. One may in principle improve the resolution along the line of sight by using combinations of spectral lines, whose contribution functions are slightly shifted relative to each other, but this improvement can hardly exceed one order of magnitude. Therefore the observed quantities will always represent ensemble averages over distributions of unresolved structures. The diagnostics of the intrinsic properties of the elements that make up such ensembles is a formidable challenge. It is however a challenge that non-solar astronomers are well familiar with, since for much more distant objects nobody can be misled to believe that the physical structures are resolved.

It is therefore obvious that the history of solar magnetic field observations will not come to an end point any time soon. As much else in science it is an open-ended enterprise. The past history has seen many spectacular advances, which have given us insights about the role played by magnetic fields not only in the Sun but throughout the universe. The deepened understanding has led to new questions that could not be contemplated at the time of Hale. The future exploration of these questions on the Sun will continue to fertilize the rest of astrophysics.

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