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Solar Magnetic Fields

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Abstract. Since the structuring and variability of the Sun and other stars are governed by magnetic fields, much of present-day stellar physics centers around the measurement and understanding of the magnetic fields and their interactions. The Sun, being a prototypical star, plays a unique role in astrophysics, since its proximity allows the fundamental processes to be explored in detail. The PRL anniversary gives us an opportunity to look back at past milestones and try to identify the main unsolved issues that will be addressed in the future.

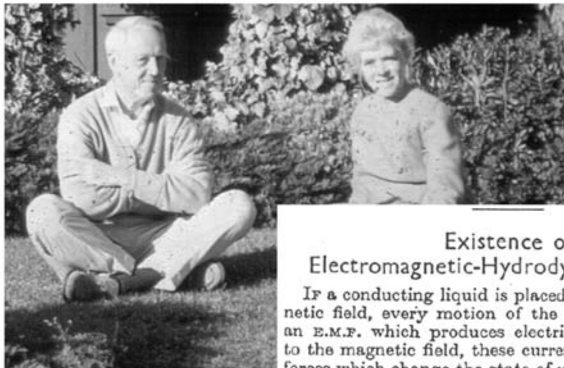
Key words. Sun—magnetic fields—polarimetry—history of science.

1. Looking back at the past century

I wish to dedicate this presentation to my dear friend Arvind Bhatnagar, whom I have known for nearly four decades, since we shared office for half a year in 1968 in Pasadena, California. Arvind later founded the Udaipur Solar Observatory, which has played an important role both for Indian science and as a partner in international projects. While remembering Arvind and celebrating the Diamond Jubilee of six decades of PRL, let me briefly recall some key personalities and events of the past century that are related to solar magnetic fields.

On the time scale of PRL, now more than six decades ago, the Swedish physicist Hannes Alfvén published a brief letter to *Nature* (Alfvén 1942, the year I was born), in which he tried to explain the origin of sunspots. A byproduct of this theory was his introduction of magnetohydrodynamic waves. Almost three decades later, in 1970, Alfvén received the Nobel prize for this, although his sunspot theory may be considered as incorrect. Many of us can take heart from this example: Do not be afraid to publish a theory that may turn out to be wrong, because it might contain some element of lasting value that may lead to a Nobel prize! In Fig. 1, Alfvén's brief, Nobel-prize winning paper is reproduced, together with a photo that I took of him (in guru position) with his wife in 1968 (the year I met Arvind, and two years before Alfvén's Nobel prize), in front of their home in La Jolla, California.

Let us look back further. More than eight decades ago, in 1923, Wilhelm Hanle in Göttingen discovered what is now called the Hanle effect (Hanle 1924), which shows how magnetic fields break the symmetry of coherently superposed quantum states (Schrödinger cat states) and cause partial decoherence that increases with the strength of the field. This discovery played a key role in clarifying and understanding the central concept of linear superposition of quantum states in the early days of quantum



Existence of Electromagnetic-Hydrodynamic Waves

If a conducting liquid is placed in a constant magnetic field, every motion of the liquid gives rise to an E.M.F. which produces electric currents. Owing to the magnetic field, these currents give mechanical forces which change the state of motion of the liquid. Thus a kind of combined electromagnetic-hydrodynamic wave is produced which, so far as I know, has as yet attracted no attention.

The phenomenon may be described by the electrodynamic equations

$$\text{rot } H = \frac{4\pi}{c} i$$

$$\text{rot } E = -\frac{1}{c}\frac{dB}{dt}$$

$$B = \mu H$$

$$i = \sigma(E + \frac{v}{c} \times B);$$

together with the hydrodynamic equation

$$\partial \frac{dv}{dt} = \frac{1}{c}(i \times B) - \text{grad } p,$$

where σ is the electric conductivity, μ the permeability, ∂ the mass density of the liquid, i the electric current, v the velocity of the liquid, and p the pressure.

Consider the simple case when $\sigma = \infty$, $\mu = 1$ and the imposed constant magnetic field H_0 is homogeneous and parallel to the z-axis. In order to study a plane wave we assume that all variables depend upon the time t and z only. If the velocity v is parallel to the x-axis, the current i is parallel to the y-axis, and produces a variable magnetic field H' in the x-direction. By elementary calculation we obtain

$$\frac{d^2H'}{dz^2} = \frac{4\pi\partial}{H_0^2}\frac{d^2H'}{dt^2},$$

which means a wave in the direction of the z-axis with the velocity

$$V = \frac{H_0}{\sqrt{4\pi\partial}}.$$

Waves of this sort may be of importance in solar physics. As the sun has a general magnetic field, and as solar matter is a good conductor, the conditions for the existence of electromagnetic-hydrodynamic waves are satisfied. If in a region of the sun we have $H_0 = 15$ gauss and $\partial = 0{\cdot}005$ gm. cm.$^{-3}$, the velocity of the waves amounts to

$$V \sim 60 \text{ cm. sec.}^{-1}.$$

This is about the velocity with which the sunspot zone moves towards the equator during the sunspot cycle. The above values of H_0 and ∂ refer to a distance of about 10^{10} cm. below the solar surface where the original cause of the sunspots may be found. Thus it is possible that the sunspots are associated with a magnetic and mechanical disturbance proceeding as an electromagnetic-hydrodynamic wave.

The matter is further discussed in a paper which will appear in *Arkiv för matematik, astronomi och fysik*.

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Figure 1. Hannes Alfvén's Nobel-prize winning *Nature* paper from 1942. At upper left, he sits with his wife outside their home in La Jolla, summer of 1968.

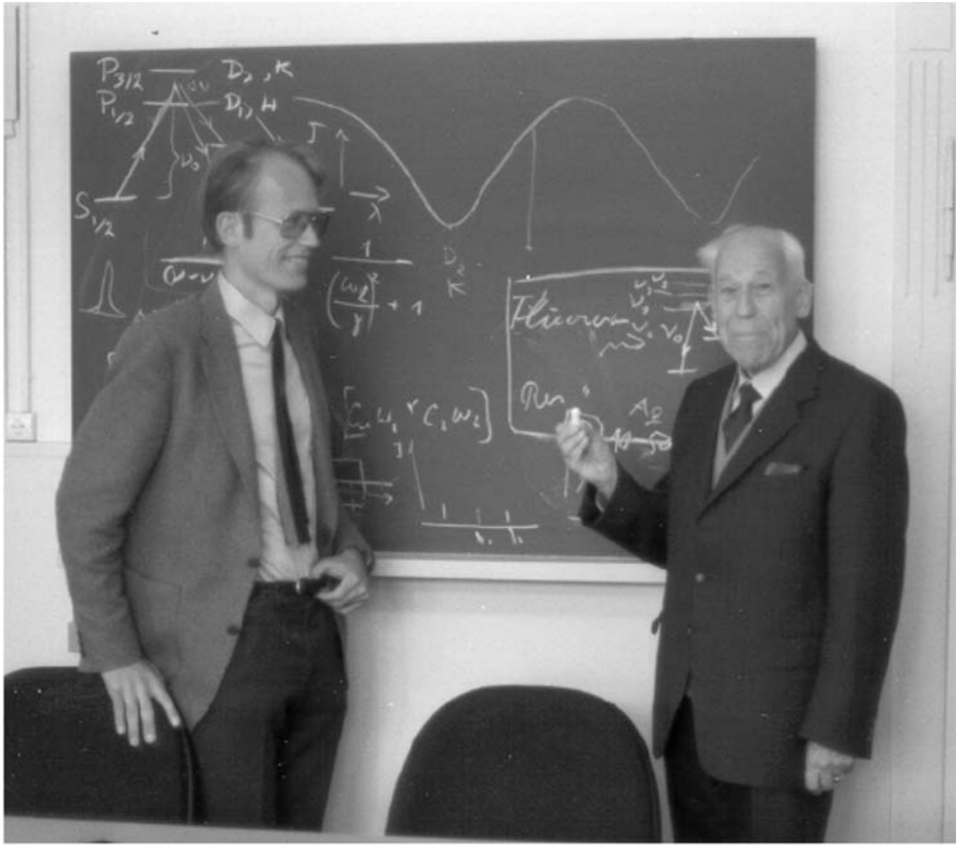

Figure 2. Wilhelm Hanle in my office at ETH Zurich in 1983, on the occasion of the 60th anniversary of his effect.

mechanics. In 1983, on the occasion of the 60th anniversary (Diamond Jubilee) of his effect, Hanle visited me at ETH Zurich (cf. Fig. 2). He was very excited that his effect was now, many decades after its discovery, being applied in astrophysics for the diagnostics of magnetic fields. The great value of the Hanle effect in astrophysics is that it provides information on magnetic fields in parameter domains, where the Zeeman effect is insensitive or even blind.

Nearly hundred years ago, the Zeeman effect was introduced to astrophysics for the first time by George Ellery Hale, who used it at Mt Wilson to discover magnetic fields in sunspots (Hale 1908). Since the introduction of the photoelectric magnetograph half a century ago (Babcock 1953), the Zeeman effect is regularly used to map solar magnetic fields and to study their evolution.

One of the giants in theoretical solar physics during the past several decades has been Gene Parker, who among many other things explained the supersonic solar wind and the principles of the solar dynamo. Figure 3 shows him at a COSPAR meeting in Tokyo in 1968 together with several other key persons in solar magnetic field work, like Bob Howard and John Wilcox, who initiated and developed fundamental synoptic programs for the Sun's magnetic field.

Figure 3. Gene Parker and fellow solar magnetic field fans in Tokyo, 1968.

2. Evolution of the fields

Macroscopic magnetic fields, on scales ranging from galaxies to planets, are believed to be produced by dynamo processes. The Sun is a prototypical dynamo that can be explored in detail. Like the galactic and planetary dynamos, the solar dynamo embodies the interaction between magnetic fields, turbulent convection, and rotation. Convection enhances the diffusion of the magnetic field lines by many orders of magnitude and transports angular momentum, which makes the rotation differential. The rotation breaks the left-right symmetry of the turbulence through the Coriolis force and makes the convective motions cyclonic, with opposite helicities in the two hemispheres. The differential rotation winds up the frozen-in field lines of an initial poloidal field to create a toroidal field. The cyclonic turbulence twists this toroidal field to regenerate a poloidal field. Through the turbulent diffusion, field lines get transported globally from local sources.

The resulting dynamo-produced magnetic field represents an oscillation between a poloidal and a toroidal state. The oscillation period is 22 yr (the Hale cycle), with sign reversal of the field every 11 yr. The sunspots represent portions of the toroidal field that have been carried up to the surface by the buoyancy forces. Therefore they appear as bipolar pairs oriented in the E–W direction, which have opposite polarity orientations in the two hemispheres. Each new 11-yr cycle the polarity orientations are reversed. These polarity rules are called Hale's polarity law, which finds a natural explanation in terms of the mentioned dynamo scenario.

The evolving polar fields reach a maximum flux around the time of minimum sunspot activity, and represent a global N–S magnetic dipole with opposite polarities of the N and S polar caps. The polarity is the same as the polarity of the leading (W) portion of bipolar sunspot groups in the same hemisphere. The polar fields reverse sign around the time of maximum sunspot activity. This reversal is, however, not synchronized between the N and S poles, a time difference of up to 2 yr is common.

As the Sun rotates with a period of approximately 27 days, we can build synoptic maps from the longitude band around the central meridian of each daily magnetogram to obtain the field distribution for all latitudes and longitudes. Such maps show a polarity pattern that is dominated by the magnetic fluxes in the sunspot latitude belts, with young, compact bipolar regions mixed with older, more dispersed bipolar flux that has been distorted by differential rotation. Due to the limited spatial resolution of such representations, however, very compact bipolar regions with much wider latitude distributions, like the numerous ephemeral active regions or the still smaller and more numerous intranetwork regions, are filtered out by the spatial smearing window.

Similar to the modal analysis of helioseismology, one way of exploring the global evolution of solar magnetic fields is to decompose the observed pattern in the synoptic maps into spherical harmonics, and then do time series analysis of the harmonic coefficients (Stenflo & Vogel 1986; Stenflo & Güdel 1988). The dominating property revealed by this analysis is a strict parity selection rule: The axially symmetric modes (with $m = 0$) are governed by the fundamental 22-yr period only when the parity is odd (the spherical harmonic degree l is odd, which means that the magnetic pattern is anti-symmetric with respect to reflections in the equatorial plane). The 22-yr period is practically absent in the even modes. Dynamo theories allow both odd and even modes to be excited, and it is not clear why the Sun has settled for such a strict choice of parity.

Although the general dynamo framework is not in serious doubt, many unanswered questions remain, mainly because of the complexity in trying to model magnetoconvection inside the Sun. The currently prevailing view is that most of the dynamo action takes place at the bottom of the convection zone, where the flux can be stored long enough before floating up to the surface. It is not clear how the Sun rids itself of all the magnetic flux that is built up each 11-yr cycle. Statistically the removal must be done as fast as the production rate.

3. Small-scale structuring

Magnetoconvection produces structuring over a dynamic range that covers many, possibly ten, orders of magnitude, from the global scales that govern the large-scale evolution of the 22-yr magnetic cycle, to the diffusion scales where the fields are destroyed. While we can resolve about four orders of magnitude of this scale spectrum, from 10^6 to 100 km, most of the structuring exists in the regime that will remain spatially unresolved in the foreseeable future. Fundamental physical processes occur at these unresolved scales, related to the emergence and destruction of flux, the heating processes and wave generation, and the fundamental turbulent processes leading to the fractal appearance of the structuring. Therefore spatially resolved observations always need to be combined with indirect diagnostics that provide information about the unresolved domain, something that is unfortunately often ignored.

The boundary between the resolved and unresolved domains gradually shifts towards smaller scales as advances in the resolving power of the instruments are made. Four decades ago, when I did the observations for my PhD with the magnetograph at the Crimean Astrophysical Observatory in 1965–66, I noticed how the field strengths went up when the spectrograph slit size used for the observations was decreased (in height). The question therefore arose what the field strengths would be if we would have infinitely high resolution. This question of course could not be answered by direct observations, so the line-ratio technique was developed, which showed that more than 90% of the net quiet-Sun magnetic flux through the resolution elements had its origin in magnetic fields with strengths of 1–2 kG, although the apparent field strengths (as averaged over the resolution element) were only a few G (cf. Stenflo 1973, 1994; Stenflo *et al.* 1984). This result implied highly intermittent magnetic fields with tiny filling factors, which led to a whole industry of theoretical modelling in terms of narrow flux tubes embedded in a largely field-free atmosphere.

While the line-ratio technique did not provide direct information on the flux tube size, comparison with the number densities of spicules and bright points suggested that the flux tube diameters would be of order 100–300 km (Stenflo 1973). At that time this was far below the resolution limit of the existing telescopes. Several decades later the observational techniques have now advanced such that, with the help of image restoration and adaptive optics, we are beginning to actually resolve these kG flux tubes, which are being considered as basic building blocks of solar magnetism. Theoretical concepts of convective collapse of flux tubes (Parker 1978; Spruit 1979; Spruit & Zweibel 1979) have provided an explanation for the kG field strengths. Various observations, in particular with infrared lines (Solanki *et al.* 1996) have given support to the convective collapse mechanism while also showing the existence of a family of weaker flux tubes that had been predicted by Venkatakrishnan (1986).

Still the idealized flux tube scenario has been unsatisfactory, since it suggests that close to 99% of the photospheric volume (outside the kG flux tubes) would be field-free, which is nonsensical, since in the highly conducting and turbulent solar plasma magnetic fields must be ubiquitous. The circumstance that the magnetograms look empty between the kG flux fragments must either mean (i) that the field in the apparently empty regions is weaker than the noise threshold in the magnetograms, or (ii) that the field strength is above that threshold, but the field polarities are mixed on scales smaller than the spatial resolution used. By using the Hanle effect we now know that alternative (ii) is the correct one, and that the "hidden" field in the seemingly empty regions is actually relatively strong, of order 30–60 G throughout the volume (in contrast to the flux tube 1–2 kG occupying on average about 1% of the volume).

The Hanle effect is a coherency phenomenon that only occurs when coherent scattering contributes to the line formation. It represents all magnetic-field induced modifications of the scattering polarization. It has different field sensitivity and symmetry properties than the ordinary Zeeman-effect polarization. Thus the Hanle effect is sensitive to weaker fields, to horizontal fields in the solar chromosphere, and to small-scale fields with randomly mixed polarities within the spatial resolution element. The Hanle and Zeeman effects therefore complement each other. In particular, the Hanle effect can reveal the spatially unresolved "hidden" turbulent flux between the kG flux tubes (Stenflo 1982; Faurobert-Scholl 1993; Faurobert-Scholl *et al.* 1995; Stenflo *et al.* 1998), while the Zeeman effect is "blind" to these fields. The Stokes vector images in Fig. 4 show examples of Hanle signatures.

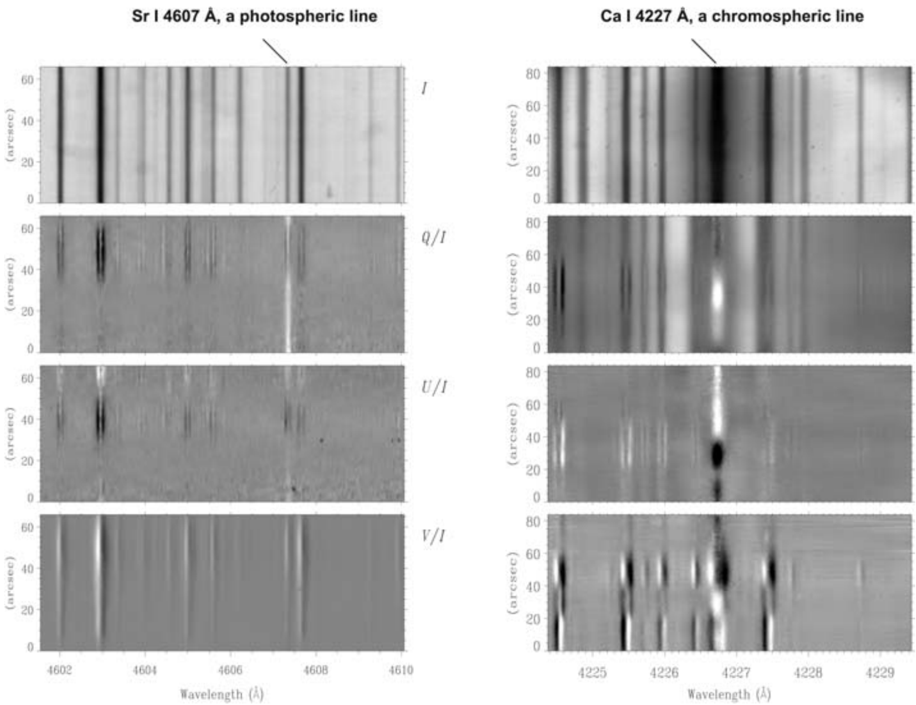

Figure 4. Recordings of the Stokes vector (the intensity I and the three fractional polarizations Q/I, U/I, and V/I) illustrating polarization signatures of the Hanle effect. The photospheric Sr I 4607 Å line and the chromospheric Ca I 4227 Å line exhibit strong linear polarization due to coherent scattering, which in the presence of magnetic fields gets modified by the Hanle effect (seen as spatial variations of Q/I and U/I along the slit). The surrounding spectral lines display the usual transverse Zeeman effect in the linear polarization (Stokes Q/I and U/I), the longitudinal Zeeman effect in the circular polarization (Stokes V/I). The recordings were made with the Zurich Imaging Polarimeter (ZIMPOL, cf. Povel 1995; Gandorfer *et al.* 2005) at the McMath-Pierce facility (Kitt Peak).

When looking at the world with our diagnostic tools, we see filtered versions of reality. When we put on our "Zeeman goggles", we see the contributions from the kG flux tubes, but filter out the turbulent fields in between. When on the other hand we put on our "Hanle goggles", we see the turbulent fields but not the kG flux tubes. We, however, increasingly realize that these two filtered versions of reality are merely two essential aspects of solar magnetism. A more unified, comprehensive view leads us to a reality that is fractal-like (Stenflo & Holzreuter 2003; Stenflo 2004). This view is supported by numerical simulations of magnetoconvection (Janssen *et al.* 2003). The pattern of quiet-Sun magnetic fields appears to maintain a high degree of self-similarity as we zoom in on ever smaller scales, as illustrated in Fig. 5. Instead of being limited to the idealized dichotomy of flux tubes and turbulent fields we need to work with probability distribution functions (PDFs) like in magnetoconvective theory. Application of PDFs to the interpretation of Hanle effect observations shows that the apparently field-free regions in solar magnetograms are filled with turbulent magnetic fields that carry magnetic energy that is significant for the overall energy balance of the solar atmosphere (Trujillo Bueno *et al.* 2004).

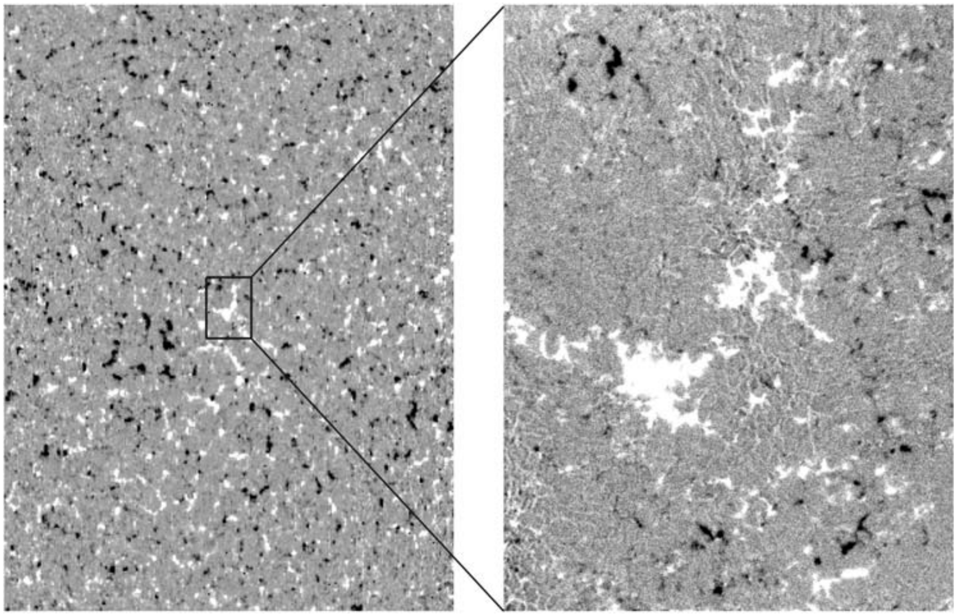

Figure 5. Illustration of the fractal-like pattern of magnetic fields on the quiet Sun. The rectangular area covered by the left map (from Kitt Peak) is about 15% of the area of the solar disk, while the map to the right (from the Swedish La Palma telescope) covers an area that is 100 times smaller. Bright and dark areas correspond to magnetic flux of positive and negative polarities, separated by grey voids of seemingly no flux. Analysis of Hanle-effect observations at IRSOL (Istituto Solari Locarno) of atomic and molecular lines have shown that these grey regions are actually no voids at all, but are teeming with turbulent magnetic fields.

4. Outlook

Synoptic programs are indispensible for learning about the global properties of the Sun. The program of daily magnetograms pioneered at Mount Wilson and extended at Kitt Peak has given us a unique dataset that now spans several solar cycles. From this we have learnt how the global evolution of the magnetic field pattern exhibits remarkable symmetries that constrain the nature of the dynamo. A new, significantly extended synoptic program, SOLIS, is now being implemented by the National Solar Observatory (USA), which will add a number of new aspects to the continued dataset, in particular vector magnetic field maps. A very important complement to the synoptic magnetic data comes from the MDI instrument on SOHO, which has provided us with the best-quality sequence of full-disk magnetograms for more than a solar cycle now.

Observations with improved angular resolution in combination with indirect diagnostics have shown that the magnetic structuring extends from the global scales towards the diffusion scales far below the telescope resolution. There is a remarkable degree of self-similarity over the various scales, indicating a fractal-like nature. A key to physical understanding may lie in the scales we are just beginning to resolve (the dimensions of the photon mean free path and the pressure scale height). The diagnostic methods to explore the unresolved scales are being extended, in particular through applications of the Hanle effect. The interpretation of these indirect diagnostic data make use of idealized, parameterized models. The task of the interpretation is to determine the free parameters of the model (which for instance could describe the analytical form of the PDF distribution function). The choice of such interpretative models is guided by numerical simulations of magnetoconvection. Although such numerical simulations provide important guidance, they in turn need to be guided by observations, since the dynamic range that they can cover in any foreseeable future is only a small fraction of the full dynamic range of scales (possibly something like ten orders of magnitude) that are part of the Sun's magnetoconvection.

We may expect dramatic observational advances in the coming years. Some of the most burning questions concern the small-scale evolution of the magnetic field. The Hinode satellite offers unprecedented possibilities to explore this small-scale evolution and its relation to the thermodynamics. New ground-based facilities (SST, GREGOR, ATST, etc.) will allow resolution of the critical scales of the photon mean free path and the pressure scale height. It is important to combine these advances of high-resolution direct observations with the new opportunities that are now opening up to explore the spatially unresolved scales via the Hanle effect. Another new development is that coronal magnetic fields are becoming measurable (from ground and from space). The interpretation of all these new observations will be greatly aided by the significant advances that can be expected in the numerical simulation of magnetoconvection and other MHD processes.

Let me end by summarizing what I consider to be some of the most important observational questions that we need to answer to understand the operation of the solar dynamo. They concern the emergence, decay, and removal of the photospheric magnetic flux. In particular: What is the fate of all the emerged magnetic flux? It has to be removed on the solar cycle time-scale and statistically be in equilibrium with the emergence rate, otherwise the photosphere would quickly be choked with undisposed magnetic flux. We know that as we go from active regions to ephemeral regions and still smaller scales, the emergence rate increases dramatically, but it is not so easy to see how one can get rid of the flux at such tremendous rates. Which is the main process? Basically we need to determine the relative contributions of the following three alternatives: (i) Cancellation of opposite polarities (reconnection). (ii) Flux retraction (reprocessing in the convection zone). (iii) Flux expulsion (and the role of CMEs).

In spite of decades of hard work we still know practically nothing about the relative roles of these processes. With the new observational tools, however, we are on the verge of significant progress in this fundamental area.

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