Magnetic Fields across the Hertzsprung-Russell Diagram
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Small-scale Photospheric Structure of the Solar Magnetic Fields outside Sunspots

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Abstract. The magnetic field in the Sun's photosphere is highly filamented and structured on scales ranging from 100 km or less to the size of sunspots (multiple 10,000 km). The main magnetic structure in these layers is described as a flux tube. Six orders of magnitude in magnetic flux separate the smallest flux tubes from the largest. Whereas small flux tubes differ remarkably from large flux tubes in their brightness, they have surprisingly similar field strengths. These and other observed properties of solar magnetic features are reviewed, with the emphasis being on non-spot fields (i.e. smaller flux tubes). The connection of these magnetic features with solar irradiance variations is also briefly touched upon.

1. Introduction

A magnetogram (Fig. 1) of the Sun reveals magnetic field distributed over much of the solar surface. Large bipolar active regions lying on both sides of the solar equator are particularly prominent, but even the so-called quiet Sun is pockmarked with magnetic features composing the magnetic network. One of the most fascinating aspects of the solar magnetic field is its filamentation, with most of the magnetic flux visible in normal magnetograms being concentrated on a small fraction of the solar surface.

The smallest magnetic structures that can be resolved lie at the current limit of spatial resolution (approximately 0.2″, corresponding to roughly 150 km on the solar surface, e.g. Keller 1992) and there is evidence that magnetic features with even smaller sizes exist (e.g. Lin 1995, Solanki et al. 1996). The largest coherent magnetic structures seen in the photosphere are sunspots. Remarkably, the magnetic structures from the narrowest filament to the largest sunspots can be reasonably described by a single theoretical idealisation, the flux tube (or tight bundles of flux tubes, see Del Toro Iniesta, Sánchez Almeida, these proceedings).

In the photosphere (the layer in which the magnetic field is best observed) the filamentation is such that we have discrete flux tubes with a field strength of 1000–2000 G, surrounded by gas with a magnetic field that is weaker by orders of magnitude. The field expands and becomes more homogeneous with height, so that in the higher layers of the solar atmosphere (the upper chromosphere, transition region and corona) the field fills all the available space and many of the flux tubes are bent to produce loops.

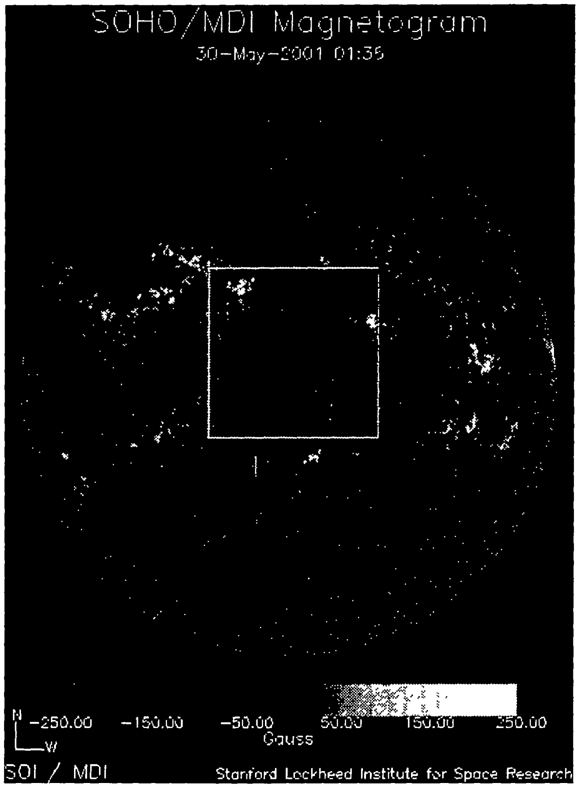

Figure 1. Magnetogram or map of the longitudinal component of the magnetic field of the whole solar disc recorded by the Michelson Doppler Imager (MDI). Regions exhibiting no net flux appear grey, while white and black indicate magnetic flux with opposite polarity.

This paper gives an introductory review of the observed properties of the smaller flux tubes, i.e. those not visible as dark sunspots on the solar surface. These are the features producing most of the signal in the magnetogram plotted in Fig. 1. To put them into perspective I begin by comparing them with sunspots.

2. Sunspots compared with magnetic elements

Flux tubes span a huge range of sizes, with the largest sunspots covering up to a million times the area of the smallest known magnetic elements. Some of the properties of these extreme types of flux tubes reflect this difference. Thus, sunspots are dark, magnetic elements are bright. The brightness increases gradually as the flux tube area decreases, with smaller spots and still smaller pores being brighter than larger sunspots, until at a diameter below approximately 300–400 km the flux tubes become brighter than the surrounding "field-free" photosphere (Fig. 2).

In other respects, however, flux tubes of almost all sizes are remarkably similar. Thus, as illustrated in Fig. 3, over almost six orders of magnitude of cross-sectional area (i.e. magnetic flux) the flux tubes have a field strength (averaged over their cross-sections) of 1.2–1.7 kG (Stenflo & Harvey 1985; Zayer

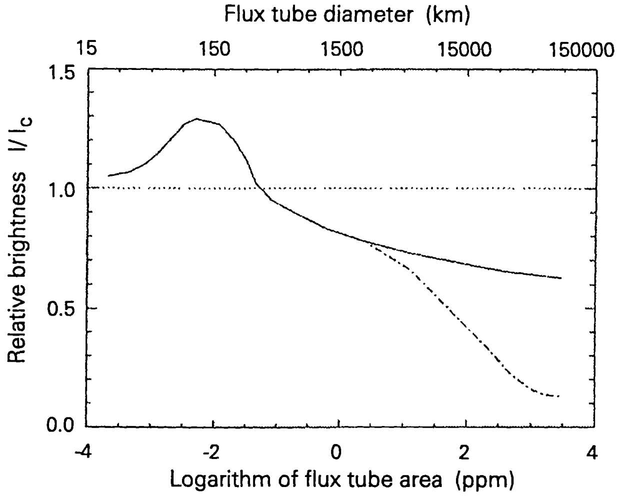

Figure 2. White-light brightness of magnetic features relative to 'quiet' Sun brightness vs. the (logarithmic) area of magnetic features in units of 10^{-6} times the solar hemispheric area (lower axis) and their diameter (upper axis). The solid line represents the brightness averaged over the whole flux tube, i.e., over both umbra and penumbra for sunspots. The dot-dashed line represents the brightness of the umbra only.

et al. 1990; Rüedi et al. 1992; Rabin 1992; Martínez Pillet, Lites, & Skumanich 1997; Bernasconi 1997). This implies that over such a large range of flux the field strength changes by less than a factor of approximately 1.3–1.4 (Solanki & Schmidt 1993). One should note that the often much larger field strengths of 3 kG quoted for sunspots refer to peak field strengths in the umbra. Since for the spatially unresolved magnetic elements we can only determine the field strength averaged over the cross-section of the flux tube this is the quantity we need to compare in the case of sunspots as well. Only at the smallest fluxes is there evidence for a decrease in the field strength (e.g. Lin 1995, Solanki et al. 1996), right down to equipartition with the convection (i.e. magnetic energy density equals the kinetic energy density). This corresponds approximately to a field strength of 200-400 G in photospheric layers.

The convection is hence far too weak to provide the force that keeps the kG fields found in normal flux tubes concentrated. All the data, however, point to the gas pressure gradient at the flux tube boundary as the dominant force that keeps flux tubes from spreading. By lowering the gas pressure within the flux tube sufficiently the sum of gas and magnetic pressure within the tube can be made to match the external gas pressure. In particular, the data reveal that the field strength decreases with height in a manner compatible with pressure balance in a hydrostatically stratified atmosphere (i.e. roughly exponentially). Since the total amount of magnetic flux in a tube is independent of height, this implies that the field expands roughly exponentially with height as well. This expansion continues to a height at which neighbouring flux tubes merge. Above the merging height the magnetic pressure within the flux tube is increasingly bal-

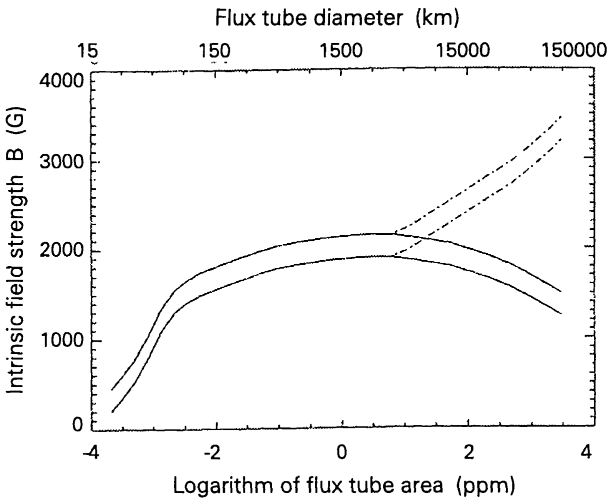

Figure 3. Intrinsic field strength B of magnetic features vs. the (logarithmic) area of their cross section (lower axis, see Fig. 1) and their diameter (upper axis). The solid lines roughly enclose the observed range of values of the field strength averaged over the whole flux tube, including over both umbra and penumbra for sunspots. The dot-dashed lines represent the maximum field strength in the umbra.

anced by the magnetic pressure in the neighbouring tube, so that the magnetic field becomes successively more homogeneous in strength above this height.

It turns out that this expansion is remarkably similar for small and large flux tubes. Thus, in the photosphere magnetic elements and sunspots expand by the same *relative* amount: they double their horizontal linear size roughly every 300 km in height (Solanki et al. 1999). This remarkable similarity between flux tubes carrying magnetic flux that differs by almost 6 orders of magnitude is still unexplained.

The number of flux tubes present on the solar surface increases with decreasing size. For sunspots this distribution can be easily determined and turns out to be lognormal in shape (Bogdan et al. 1988). The decrease in numbers at the smaller sizes stems from the fact that smaller flux tubes do not manifest themselves as sunspots. Determining the size distribution of magnetic elements is more difficult since they are rather close to the spatial resolution limit in size. Nevertheless, indirect considerations support this view. Firstly, the amount of total flux in weak and strong fields is roughly equal (Meunier, Solanki, & Livingston 1998). Secondly, there is less flux per thin, weak-field flux tube than per thicker strong-field tube (Solanki et al. 1996). Ergo, more of the thinner flux tubes are present.

Note that there is evidence for a very weak (tens of G) tangled or turbulent magnetic component from Hanle-effect measurements (Faurobert-Scholl et al. 1995; Stenflo, Keller, & Gandorfer 1998). Although such a turbulent field may well carry a considerable fraction of the total solar magnetic flux, its influence on the solar gas is expected to be far below that of the strong flux tubes, since its energy density is much smaller. Such a field is not discussed here any further.

3. Properties of magnetic elements

3.1. Magnetic orientation

Magnetic elements are characterized by more than their field strength. It is of considerable interest to know whether the field is oriented mainly vertically, or more horizontally. Theoretical considerations suggest that the highly evacuated flux tubes with strong fields should stand practically vertical due to buoyancy (Schüssler 1986), while simulations show them to be periodically inclined by the action of strong horizontal motions (Steiner et al. 1998). Observations reveal the strong fields to be mainly vertical (Martínez Pillet et al. 1997; Bernasconi 1997; Lites, Skumanich, & Martínez Pillet 1998; Sigwarth et al. 1999), while the weaker fields are closer to being horizontal according to Lites et al. (1998) and Sigwarth et al. (1999). In particular, Lites et al. (1998) find a linear relationship between inclination and field strength. Such a linear relationship is also exhibited by sunspots (e.g. Solanki, Walther, & Livingston 1993; Stanchfield, Thomas, & Lites 1997). Note however, that the weak fields seen by Lites et al. (1998) are freshly emerged, i.e. they may appear horizontal due to the fact that we are seeing the top of an Ω-shaped loop passing through the photosphere. Further observational evidence for or against such a relationship would be extremely useful.

A roughly linear relationship between magnetic inclination and field strength is also obtained from recent 2-D MHD simulations. In these the vertical fields are concentrated in the downflow lanes of the granulation, while the weak horizontal fields are located above the granules, where the flow is mainly horizontal (Gadun et al. 2001). Hence the field and flow (which are linked through the fact that the medium is ionized and the field thus frozen into the plasma) settle for a geometry which allows them to co-exist with a minimum of interference.

Whether this theoretical linear relation (present on the scale of the granulation) provides the correct explanation for the observed relation (seen on large scales) is currently unclear and in need of further study.

3.2. Thermal structure and brightness

The brightness and temperature structure of magnetic elements gives insight into the energy transport mechanisms acting within them.

Whereas sunspots and in particular the somewhat smaller pores are best seen in continuum radiation and are less visible in the cores of strong spectral lines, magnetic elements are far less prominent in continuum radiation than in lines, at least when seen at the centre of the solar disc. This already suggests that the temperature gradient within magnetic features is different from that in the quiet Sun. Note, however, that a part of the increased contrast produced by magnetic elements in images taken in the cores of spectral lines may be due to the greater temperature sensitivity of some spectral lines or due to the expansion of the flux tubes with height.

A more quantitative estimate of the temperature stratification within magnetic elements is obtained by modelling the Stokes profiles of numerous spectral lines. Such models, employing LTE (Stenflo 1975; Chapman 1977; Solanki 1986; Bellot Rubio, Ruiz Cobo, & Collados 1997, 1999, 2000; Frutiger & Solanki 1998, 2001) and NLTE radiative transfer calculations (Bruls & Solanki 1993; Briand & Solanki 1995), do indeed show magnetic elements to be hotter than the average

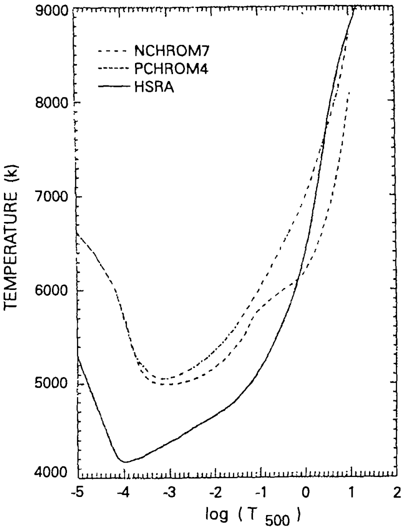

Figure 4. Temperature T vs. logarithmic continuum optical depth at 500 nm, $\log(\tau_{500})$, of atmospheres for magnetic elements in active-region plages (dashed line) and in the quiet-sun network (dot-dashed line), as well as the quiet Sun model HSRA (solid line).

quiet Sun mainly in the middle and upper photosphere. The models based on NLTE calculations also reveal that within magnetic elements the chromospheric temperature rise starts deeper in the atmosphere than in the non-magnetic atmosphere (Fig. 4).

Another interesting result is that although magnetic elements of different sizes have rather different temperatures in the lower photosphere (where the continuum is formed, Hirayama 1978; Solanki 1986) their temperature stratifications in the chromosphere are almost indistinguishable (e.g. Briand & Solanki 1995; see Fig. 4). This suggests that different mechanisms govern the thermal stratification in the deeper and higher layers of magnetic elements. The former depends strongly on flux tube size, while the latter less so.

Consider now the physics influencing the thermal structure in the deeper layers. Overturning convection is inhibited by a sufficiently strong magnetic field, so that radiation plays a much stronger role in transporting energy within magnetic features than outside them (e.g. Spruit 1976; Deinzer et al. 1984). Because of the significant pressure exerted by the magnetic field, magnetic elements are evacuated, so that the optical depth unity level ($\tau = 1$) is reached at greater depth (called Wilson depression in analogy to a similar feature in sunspots). Hence magnetic elements are heated not just from below, but also by the energy radiating from the walls (mainly between $\tau = 1$ in the external atmosphere and in the flux tube). Since the field strength is almost independent of flux tube size (Sect. 2) to first order the Wilson-depression is too. Hence the ratio of radiative energy flux entering from the sides to that from below decreases like $1/r$, where r is the radius of the flux tube (assumed to be cylindrically symmetric). Consequently, whereas the excess horizontal radiative flux can more than compensate for the reduced convective flux in small flux tubes, it falls well short for large tubes. This explains to first order the dependence of temperature on size in the lower photosphere (e.g. Grossmann-Doerth et al. 1994). The independence of temperature on size in the upper photosphere and chromosphere implies that another heating mechanism must be acting there. One possibility is the dissipation of waves travelling along the field lines. So far, however, little direct evidence has been found for this.

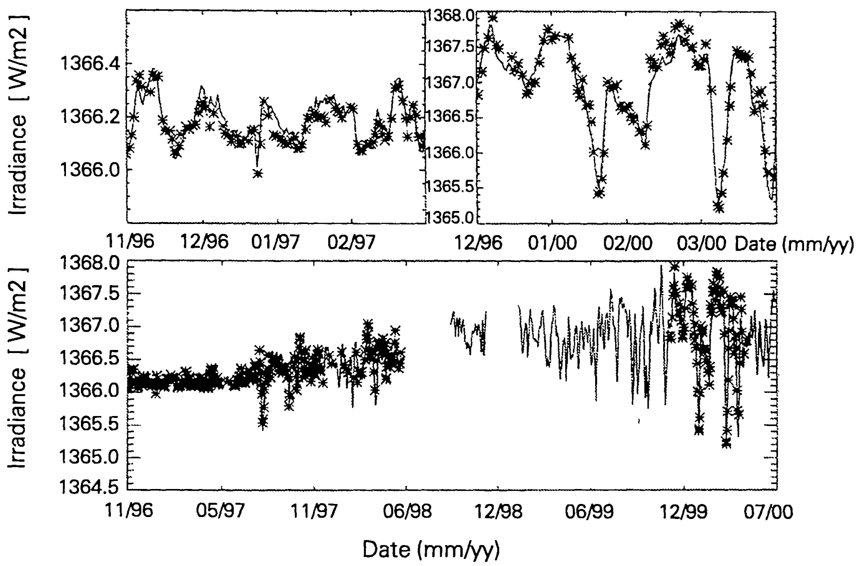

Figure 5. Reconstruction (stars) of total solar irradiance for roughly 700 individual days between the end of 1996 and mid 2000, i.e. from the onset of solar cycle 23 right into its maximum. The irradiance record measured by VIRGO is represented by the solid line. The two panels on the top show a zoom-in to the beginning (left panel) and the end (right panel) of the complete data set (lower panel), respectively. The model is able to reproduce both, short-term variations on time-scale of days to weeks as well as the longer-term increase of solar irradiance between activity minimum and maximum.

4. Magnetic elements and solar irradiance variations

Although most of the physical questions concerning magnetic elements are related to their local physical properties, these can in some cases affect the global properties of the Sun. An important example is the total irradiance of the Sun, i.e. the energy flux of the Sun integrated over all wavelengths as measured above the Earth's atmosphere. This exhibits prominent 1-2 week long dips and is also modulated by the solar cycle. The dips are well-correlated with the passage of (groups of) dark sunspots across the solar disc resulting from solar rotation. Apparently, the energy flux blocked by sunspots does not reappear elsewhere on the solar surface at short timescales (Spruit 1982). Indeed, the recent rediscovery of bright rings around sunspots (Rast et al. 2000) only confirms this, since only a minute fraction of the energy flux blocked by the sunspot is released by the bright ring. More surprisingly perhaps, the total irradiance is on average 0.1% higher during activity maximum, i.e. when the number of dark sunspots is large (e.g. Fröhlich 2000). However, the flux in the non-spot fields also increases from activity minimum to maximum. This increase is larger than that of the flux in sunspots, because sunspots live only for days to weeks, before decaying. The decay product of sunspots are small magnetic elements. Hence the magnetic flux that initially emerges in the form of a dark sunspot and contributes to a darkening of the Sun is soon converted into magnetic elements and hence contributes to the brightening. In addition, fresh flux appears in the form of magnetic elements at the solar surface at an increased rate during activity maximum.

Although each magnetic element only contributes a minuscule amount of excess radiative flux, the millions of elements on the solar surface not only compensate for the energy blocked by sunspots, but also produce the observed excess of 0.1%. This can be modelled with great precision using magnetograms (from which the amount of magnetic flux at the solar surface at a given time is determined) and models of the atmospheric structure of magnetic elements and sunspots. In Fig. 5 the results of such a model due to Fligge et al. (2000) are compared with the total irradiance observed between 1996 and 1999 by the VIRGO instrument (Fröhlich et al. 1995) on the SOlar and Heliospheric Observatory (SOHO). The correlation between modelled and observed irradiance time series is in excess of 0.95.

5. Conclusion

It has been my aim in this presentation to provide a brief introduction to the properties and (even more rudimentarily) physics of non-spot magnetic fields on the Sun. Numerous topics have not been touched upon at all. These include the formation and destruction of magnetic elements, the emergence, spatial distribution and dissipation of magnetic flux outside sunspots as well as the dynamics within and of magnetic flux tubes. The last topic is of particular importance for chromospheric and coronal heating. More on our physical understanding of such features and their interaction with the convection is to be found in the review by Schüssler & Knölker (these proceedings).

Additional details on non-spot magnetic fields are given by, e.g., Solanki (1993), Schrijver & Zwaan (2000).

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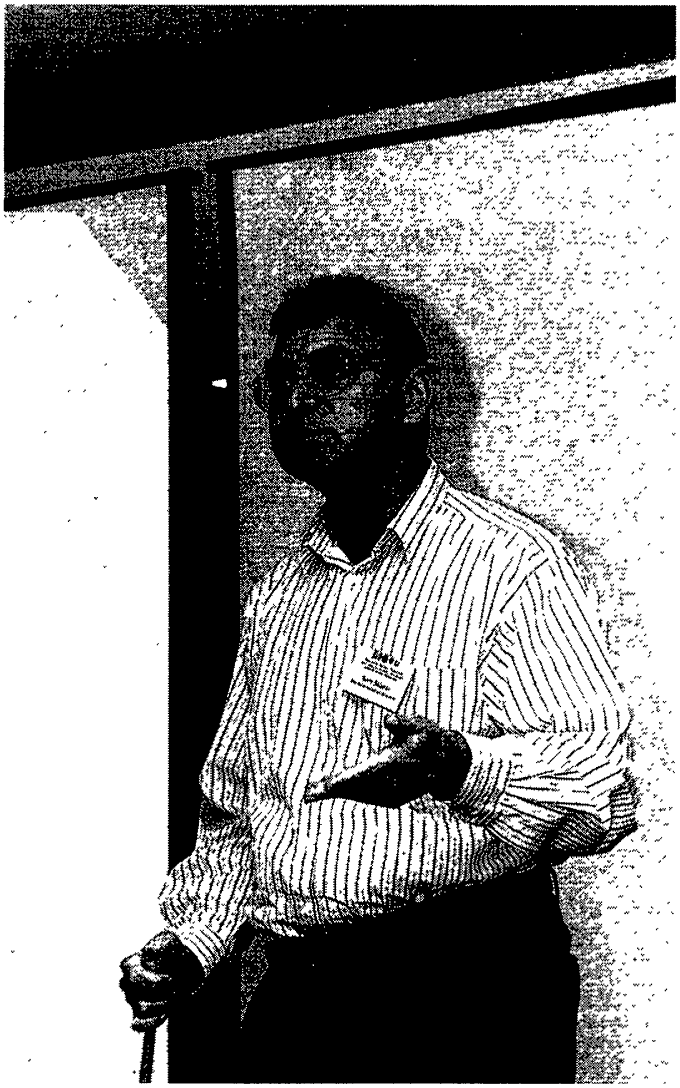

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