Magnetic fields in the solar photosphere

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Recent high resolution observations of the surface of the Sun have revealed the fine structure of a vast array of complex photospheric magnetic features. Observations of these magnetic field structures have already greatly enhanced our theoretical understanding of the interactions between magnetic fields and turbulent convection, and future photospheric observations will inevitably present new theoretical challenges. In this review, I discuss recent progress that has been made in the modelling of photospheric magnetic fields. In particular, I focus upon the complex field structures that are observed within the umbrae and penumbrae of sunspots. On a much smaller scale, I also discuss models of the highly-localised magnetic field structures that are observed in less magnetically-active regions of the photosphere. As the spatial resolution of telescopes has improved over the last few years, it has now become possible to observe these features in detail, and theoretical models can now describe much of this behaviour. In the last section of this review, I discuss some of the remaining unanswered questions.

Keywords: The Sun; solar; magnetic field; magnetohydrodynamics; photosphere; convection

1. Introduction

Modern ground-based and space-borne telescopes enable us to make detailed observations of magnetic fields at the solar surface (also known as the solar photosphere). For example, the Swedish 1 metre Solar Telescope (SST) on La Palma can resolve features down to 70km at the surface of the Sun. Such high spatial resolution is essential in order to capture the fine structure of magnetic fields in sunspots, which are the largest and therefore the most obvious photospheric magnetic features. On a much smaller scale, in less magnetically-active regions of the photosphere it is also now possible to observe highly localised concentrations of intense vertical magnetic flux (with a diameter of the order of 100km). Over the last couple of years, our understanding of all of these magnetic field structures has been further enhanced by observations that have been carried out using the Solar Optical Telescope (SOT) on board the recently-launched Hinode satellite. These observations have already presented theorists with new challenges, and further questions are likely to emerge in the near future.

It is clear that the vigourous convective motions that are observed at the solar surface play a crucial role in the evolution of photospheric magnetic fields. For this reason, the Sun is an excellent laboratory for the study of magnetoconvection, a branch of magnetohydrodynamics which describes the complex interactions between magnetic fields and convection in an electrically-conducting fluid (see, for example Proctor & Weiss 1982). A proper description of this process is essential in...
order to understand photospheric magnetic fields. Although it is not yet possible to carry out numerical simulations of magnetoconvection in realistic solar parameter regimes, idealised numerical calculations can now reproduce behaviour that can be qualitatively related to magnetic features at the solar surface. In this short article, I review some of the recent progress that has been made in the theory and observation of photospheric magnetic fields. In the next section, I focus upon the properties of sunspots. This is followed by a discussion of magnetic features away from active regions, in the quiet Sun. In the final section, I describe some of the remaining issues that have yet to be resolved.

2. Sunspots

The presence of dark spots on the surface of Sun was noted long before the invention of the telescope. Historical accounts of sunspot observations in China and Greece suggest that astronomers have been aware of the existence of these features for well over 2000 years. Telescopic observations in the 17th Century, carried out by Galileo (and others), provided the first hint that sunspots were not uniformly dark features. In fact, these observations indicated that sunspots consist of a dark umbra surrounded by a slightly brighter region called the penumbra. However, it wasn’t until the beginning of the 20th Century that the true nature of sunspots became apparent. Hale (1908) showed that sunspots are the sites of strong magnetic fields. Using the Zeeman effect, Hale measured a magnetic field-strength of approximately 3000 Gauss, which is several orders of magnitude larger than the Earth’s
magnetic field. We now know that sunspots are simply the surface manifestations of an underlying large-scale magnetic field within the Sun, which is generated and maintained by a hydromagnetic dynamo (Ossendrijver 2003). The properties of the large-scale solar magnetic field are also discussed by Silvers (2008, this volume).

In recent years, it has become possible to observe the fine structure of sunspots. Figure 1 shows a high resolution SST image of part of a large sunspot (Scharmer 2002). The dark umbral region of the spot is clearly visible in the lower part of this image. This umbra is surrounded by a well-defined penumbra, which is characterised by a complex radial pattern of bright and dark “filaments”. Magnetic field measurements within sunspots indicate that the field lines are predominantly vertical in the umbral region (i.e. perpendicular to the surface of the Sun). However the magnetic field geometry within the filamentary penumbral region is much more complicated (see, for example, Title et al. 1993). Along dark filaments within the penumbra, the magnetic field lines are nearly parallel to the surface of the Sun, dropping just below the surface towards the outer edge of the spot. On the other hand, the magnetic fields lines that are associated with the bright filaments are inclined at an angle of approximately 30° degrees to the vertical at the umbral-penumbral boundary – the angle of inclination of these field lines increases with radial distance away from the umbra. The net effect of all this is that the magnetic field in the penumbra forms a remarkable “interlocking-comb” structure. This is illustrated schematically in Figure 2. Furthermore, even within the filaments themselves, the magnetic geometry is non-trivial – recent observations suggest that the field lines in these regions are often twisted (Ryutova et al. 2008). Much more detailed accounts of sunspot observations are given by Solanki (2003) and Thomas & Weiss (2004, 2008).

Theoretical studies of magnetoconvection have shown that a strong vertical magnetic field, such as that found within a sunspot umbra, inhibits convective motions (see, for example, Proctor & Weiss 1982). Near the visible surface of the Sun convection in non-magnetic regions is characterised by a highly time-dependent network of broad warm upflows and cooler narrow downflows. The upper layers of these convective cells form a "granular" pattern at the solar photosphere. Convection of this type is just visible in the top part of Figure 1. Magnetic forces imply that such vigorous convective motions are simply not possible within a sunspot umbra. Inefficient convection implies that the surface of a sunspot is cooler (and therefore darker) than its non-magnetic surrounding. However, there is some evidence for weak convective flows within umbral regions. Within the umbra, there are highly localised features that are slightly brighter than their surroundings – these are known as umbral dots (see, for example, Sobotka et al. 1997). Recent SOT observations from Hinode (Kitai et al. 2007) indicate that these “point-like” umbral features have a typical diameter of approximately 250km (a tiny fraction of the total sunspot diameter) and a lifetime of between 4 and 20 minutes. Patterns of weak, small-scale, convective plumes have been observed in numerical simulations of umbral convection (Weiss et al. 2002; Schüssler & Vögler 2006). Furthermore, isolated convective plumes (or “convectons”) have been found in certain simplified magnetoconvection models (see, for example, Blanchflower 1999). It is therefore probable that umbral dots are the observable signatures of weak convective flows.

Observations of the development of sunspots suggest that they form from large magnetic features, known as pores, which rapidly develop penumbral structure once
the size of the pore exceeds some critical value (Leka & Skumanich 1998). The physical mechanisms that are responsible for the formation and maintenance of this penumbral structure are still not fully understood, although some plausible theories have been proposed. Highly idealised numerical simulations suggest that the edges of large pores are susceptible to a convectively-driven instability, which would naturally lead to the formation of a non-axisymmetric (i.e. penumbral-like) magnetic field configuration around the pore (Tildesley & Weiss 2004; Botha et al. 2007). Alternatively, it has been suggested that the penumbral structure may be the result of the collective instabilities of an ensemble of interacting twisted magnetic flux tubes at the edge of the umbral region (Ryutova et al. 2008). It is even less clear why the complex interlocking-comb structure of the penumbral magnetic field should be a stable configuration. Given that the material within the dark filaments should be less dense than the surrounding photospheric plasma, it is particularly surprising that the associated magnetic field lines appear to lie below the surface in the outer penumbra. Thomas et al. (2002) have argued that the small-scale convective motions at the edge of the sunspot must be playing a key role in holding down these field lines (see also Weiss et al. 2004; Brummell et al. 2008). By anchoring the edges of these dark filaments to the photosphere, this convectively-driven “flux pumping” effect provides a possible mechanism for the maintenance

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Figure 2. A schematic illustration of the magnetic field structure within the umbra and penumbra of a typical sunspot. The magnetic field lines are predominantly vertical within the umbra. Within the penumbra, some of the field-lines (those associated with the bright filaments) still have a significant vertical component, whilst those that are associated with the dark filaments are largely horizontal. Image taken from Thomas & Weiss (2004). Reprinted, with permission, from the Annual Review of Astronomy and Astrophysics, Volume 42 (c)2004 by Annual Reviews www.annualreviews.org.
of the interlocking-comb structure of the penumbra. Whilst these theories for the formation and stability of sunspot penumbral structures are certainly promising, alternative explanations for the observed penumbral structure have been proposed (see, for example, Spruit & Scharmer 2006). Therefore, it is clear that our understanding of these complex magnetic features is far from complete.

3. The quiet Sun

Although sunspots are the largest magnetic flux concentrations in the solar photosphere, they are not the only magnetic features that can be observed at the surface of the Sun. Significant quantities of magnetic flux can also be found in plage regions, which often occur near to sunspots. Recent SST observations (Berger et al. 2004) indicate that the magnetic flux in plages seems to form extended ribbon-like structures, with a peak magnetic field strength of the order of 1500 Gauss. Whilst the magnetic field in these regions is substantially weaker than that found within sunspot umbrae, it is still strong enough to exert a significant dynamical influence upon the surrounding convection. In the quiet Sun, well away from active regions, any vertical magnetic flux tends to accumulate in the downflows at the edges of the granular convective cells (Lin & Rimmele 1999). In fact, compact regions of vertical magnetic flux appear to be a common feature of intergranular lanes in the quiet Sun (Domínguez Cerdeña et al. 2003). These localised flux concentrations often show up as bright points in G-band images of the solar photosphere. The observed motion of these bright points implies that magnetic flux moves along the intergranular lanes on a convective time-scale (Berger & Title 1996). Although a broad range of magnetic field strengths is measured in these regions, the peak vertical field strengths often comfortably exceed a kilogauss (see, for example, Domínguez Cerdeña et al. 2006).

Recent Hinode observations have further enhanced our understanding of magnetic flux in the quiet Sun. In addition to the intergranular regions of vertical magnetic flux, Lites et al. (2008) have found significant quantities of horizontal magnetic flux, mostly at the edges of granules. Also using Hinode, Centeno et al. (2007) followed the evolution of a single loop of magnetic flux as it emerged at the photosphere within a granular convective cell. Observations indicated that the lower parts of this flux loop (in which the magnetic flux was predominantly vertical) were advected into the intergranular lanes by the diverging convective flows within the granule. This tendency for convection to expel magnetic flux is a well-known feature of magnetoconvection in highly-conducting fluids (Proctor & Weiss 1982), and the flux emergence and expulsion processes that were observed by Centeno et al. (2007) have already been reproduced in numerical simulations (Stein & Nordlund 2006). The observations indicate that the magnetic flux that accumulates in the convective downflows in the quiet Sun (as a result of this flux expulsion process) forms highly localised, almost point-like structures rather than the ribbon-like features that are observed in plages. This is a consequence of the fact that the mean magnetic flux density in quiet Sun regions is much smaller than the mean flux density found in plages. Diffuse magnetic regions with low flux densities do not exert a significant dynamical influence upon the surrounding convection. This implies that magnetic effects can only begin to restrict the flux expulsion process once highly-localised concentrations of magnetic flux have formed. Numerical simulations have

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Figure 3. A snapshot of a numerical simulation of an idealised model of magnetoconvection in the quiet Sun. Filled contours show the temperature variations in a horizontal plane near the upper surface – the bright regions correspond to broad warm upflows, whilst darker regions correspond to cool narrow downflows. The white contours highlight regions of intense vertical magnetic flux. These are always associated with the convective downflows.

confirmed the idea that more compact magnetic field structures tend to be favoured in regions of lower magnetic flux (Bushby & Houghton 2005; Khomenko et al. 2005; Shelyag et al. 2007). An example of an idealised model of magnetoconvection in the quiet Sun is shown in Figure 3.

Whilst the observed association between the magnetic flux concentrations and the intergranular lanes in the quiet Sun is readily explained by the process of flux expulsion, the strength of the resulting magnetic flux concentrations is more difficult to explain. Simple estimates indicate that the magnetic energy density of the observed kilogauss-strength magnetic features is an order of magnitude larger than the kinetic energy density of the surrounding non-magnetic convection. We might expect these energy densities to be (roughly) comparable if flux expulsion is the only mechanism that is responsible for the formation of these magnetic features. In the late 1970’s, numerous authors independently proposed an additional flux amplification mechanism, now commonly referred to as "convective collapse" (Parker 1978; Webb & Roberts 1978; Zwaan 1978; Spruit 1979; Unno & Ando 1979). They considered the stability of a thin vertical magnetic flux tube in static equilibrium in the solar photosphere. It can be shown that this (highly idealised) configuration is convectively unstable provided that the initial field is not too strong. The resulting motions would carry plasma vertically downwards out of the flux tube, thus reducing the internal pressure within the tube. In order to maintain a pressure balance with its non-magnetic surroundings, the tube must then collapse radially inwards.
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Figure 4. An illustration of the idealised convective collapse mechanism. Convectively-driven motions (indicated by the large arrow) drain plasma vertically downwards, away from the surface layers of the flux tube. The resulting reduction in pressure causes the magnetic feature to “collapse” radially inwards. This produces a higher concentration of vertical magnetic flux.

This leads to a rise in the magnetic field strength within the flux tube. This process is illustrated schematically in Figure 4.

Although convective collapse models provide an extremely useful insight into the process of magnetic field amplification, they are clearly highly idealised models. In the photosphere, the initial configuration of a static vertical flux tube is somewhat implausible. It is also worth noting that various physical processes have been ignored. For example, dynamical interactions between the flux tube and the surrounding convection are not considered in the standard convective collapse model. Also of importance are radiative effects (see, for example, Schüssler 1990), which will tend to accelerate convective downflows by enhancing the cooling of the surface layers of the flux tube (where horizontal convective motions are inhibited by the strong magnetic pressure). Having said that, all numerical simulations of magnetic flux intensification (e.g. Grossmann-Doerth et al. 1998; Carlsson et al. 2004; Vögler et al. 2005; Stein & Nordlund 2006; Bushby et al. 2008) have shown that the partial evacuation of magnetic regions due to vertical convective motions is responsible for the formation of strong photospheric magnetic features. Furthermore, plausible observational evidence for the convective downflows leading to magnetic flux intensification has recently been obtained using SOT on Hinode (Nagata et al. 2008). Therefore, this convective process is probably playing a crucial role in the formation of kilogauss-strength magnetic features in the quiet Sun.

Observations of the quiet Sun clearly show that a large proportion of this region is covered with localised concentrations of mixed-polarity vertical magnetic flux. The origin of all this magnetic flux is still not fully understood. One possibility is that quiet Sun magnetic fields are simply remnants of former active regions that have been reprocessed by the vigorous motions within the convection zone. An alternative possibility is that the small-scale convective motions near the visible surface of quiet Sun are themselves responsible for the generation and maintenance of the observed magnetic fields. Small-scale dynamo action of this type is possible...
Figure 5. A numerical simulation of a convectively-driven dynamo. Left: The granular convective pattern near the visible surface. Like Figure 3, brighter regions correspond to broad warm upflows, whilst darker regions correspond to cooler narrow downflows. Right: The line-of-sight component of the magnetic field. Black and white regions correspond to opposing magnetic polarities. (Image taken from Schüssler & Vögler 2008.)

if the inductive effects due to the fluid motions outweigh the dissipative effects due to magnetic diffusion. Under such circumstances, dynamo action of this type has been found in numerical simulations of convectively driven flows in a plane layer of electrically-conducting fluid (Cattaneo 1999; Vögler & Schüssler 2007; Schüssler & Vögler 2008). This is illustrated in Figure 5. In the latest calculations that have been carried out by Schüssler & Vögler (2008), the resulting magnetic field structures appear to be qualitatively consistent with the recent Hinode observations carried out by Lites et al. (2008). It should be stressed that it is currently not possible to run simulations of this type in parameter regimes that are appropriate for the solar photosphere. Furthermore, the viability of small-scale dynamo action in more realistic parameter regimes is currently unclear (Boldyrev & Cattaneo 2004; Schekochihin et al. 2004). However, dynamo action of this type provides a very attractive explanation for the appearance of mixed polarity magnetic flux in the quiet Sun.

4. Summary and future challenges

Recent advances in observational technology and techniques have revolutionised our understanding of photospheric magnetic fields. It is now possible to resolve the fine structure of magnetic features over a wide range of spatial scales, from large-scale fields in sunspot penumbrae to localised concentrations of magnetic flux in the quiet Sun. In the quiet Sun, numerical simulations have played a major role in enhancing our understanding of the convective intensification of magnetic fields. However, since it is not yet possible to carry out numerical calculations in parameter regimes that accurately reproduce photospheric conditions, the question of the origin of these magnetic features remains unresolved. Similarly, we now have plausible theories for the formation and maintenance of the complex interlocking-

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Comb structure of sunspot penumbrae. However, our current understanding of the complex magnetic geometry and convective flows in sunspots is incomplete. In this context, it is worth noting that numerical simulations of a global sunspot model are currently being carried out by Rempel and his collaborators (Rempel et al. 2008). Initial results suggest that these calculations may provide us with significant new insights into the magnetoconvective processes that occur within sunspots. Obviously, magnetic fields in the solar photosphere are coupled to the solar interior as well as regions which lie above the visible surface of Sun (such as the chromosphere). Ideally, this coupling should be taken into account when modelling photospheric magnetic features. In the last couple of years, numerical simulations have started to explore the possible interactions between magnetic fields in these regions (see, for example, Rezaei et al. 2007; Isobe et al. 2008), and such studies are likely to produce interesting results in the near future.

In summary, many aspects of photospheric magnetic fields are now well understood. However a number of unanswered questions remain. Inevitably, as observations continue to improve, new theoretical challenges will emerge.

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Born in 1978, I grew up in Leeds. Having attended Leeds Grammar School for nearly 10 years, I went on to study Mathematics at Cambridge. As a member of Clare college, I graduated with a first class degree before gaining a distinction in the Certificate of Advanced Study in Mathematics. As a postgraduate student in the Department of Applied Mathematics and Theoretical Physics at Cambridge, I completed my Ph.D. (entitled “Nonlinear dynamos in stars”) in 2003, under the supervision of Nigel Weiss. I then spent four years working in the same department as a postdoctoral research associate in the Astrophysical Fluid Dynamics group. I have recently been appointed as a Lecturer in Applied Mathematics at Newcastle University. My general areas of academic interest include fluid dynamics and magnetohydrodynamics, particularly in the context of astrophysical systems. More specifically, I am interested in solar and stellar magnetic fields, dynamo theory and magnetoconvection. In my spare time, I play the trumpet and cornet.