The Puzzling Structure of a Sunspot

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Abstract. Sunspots are characterized by the presence of a filamentary penumbra but it is only within the last few years that the fine structure of penumbral magnetic fields, and of the associated Evershed outflow, has been definitively established. High resolution observations show that bright filaments in the inner penumbra possess slender dark cores with fields and flows that are nearly horizontal, while the ambient fields are inclined at 40° to the vertical. In the outer penumbra the fields in bright and dark filaments differ in inclination by about 30° and recent observations confirm that the Evershed flow is along the almost horizontal fields in dark filaments. Moreover, these two families of field lines remain distinct. This intricate magnetic geometry poses major theoretical problems. How can such a structure be maintained and how does it originate? How do penumbral fields relate to the photospheric granulation outside the spot? What drives the Evershed flow within dark filaments? What form does convection take in the umbra, in bright filaments and in dark filaments? What causes the fine structure within bright filaments? What is the subsurface structure of a sunspot and how does it relate to outflows and inflows in the moat cell that surrounds it? Although a general theoretical picture is beginning to emerge, these questions can only be properly answered through detailed computational investigations, guided by further observations both from the ground and from space.

1. Introduction

This is an old subject that has entered upon an exciting new phase, driven by high-resolution observations. The distinction between the umbra and penumbra of a sunspot has been recognized ever since the earliest telescopic observations, four hundred years ago, by Galileo, Scheiner and Hevelius. Two centuries later, telescope technology had advanced sufficiently for William Herschel to see fine structure and for John Herschel to detect filaments in the penumbra. One hundred years ago, following the development of spectroscopy, George Ellery Hale measured the magnetic fields in sunspots by using the Zeeman effect. Later, in the sixties and seventies, finer structures were gradually revealed, first from balloon-borne telescopes (Danielson 1961a) and then from the ground (e.g. Beckers & Schröter 1969; Muller 1973). It is only within the last fifteen years, however, that features 0.1 – 0.2˝ across have been resolved, first with the Swedish Vacuum Solar Telescope and, more recently, with the aid of adaptive optics on the Dunn Telescope and the new one-meter Swedish Solar Telescope (Scharmer et al. 2002; Rouppe van der Voort et al. 2004). These new observations (see Figure 1) have transformed our understanding of the magnetic geometry of a sunspot – and, in so doing, have provided headaches for theoreticians.
Meanwhile, the last sixty years have seen major theoretical developments. The decade from 1940 to 1950 saw the invention of magnetohydrodynamics by Alfvén and the realisation by Biermann and Cowling that sunspots are dark because convection is suppressed by their magnetic fields. During the next ten years, Thompson and Chandrasekhar developed the linear theory of magnetoconvection. Then, around 1965, computation entered the field of astrophysical fluid dynamics, with the prospect of exploring nonlinear behavior. That has led to a spate of numerical experiments and detailed simulations. It is here that Bob Stein, in collaboration with Nordlund, has transformed our understanding of astrophysical convection (Nordlund & Stein 1989; Stein & Nordlund 1989, 1998, 2003).
Solanki (2003) and Thomas & Weiss (2004) have provided extended accounts of recent progress. In this brief review, I shall first describe some of the latest observations of fine structure in sunspot penumbrae. Then I shall list the important questions that are posed by these observations, before putting forward a theoretical picture that addresses some of the problems. In conclusion, I shall point ahead to the progress that we can expect over the next few years.

2. The Structure of Penumbral Magnetic Fields

It has long been known that the azimuthally averaged magnetic field in a sunspot, regarded as a function of distance from the center, falls off in strength, while its inclination to the vertical increases from zero at the center to about $70^\circ$ at the edge of the spot (Hale & Nicholson 1938; Beckers & Schröter 1969; Adam & Petford 1991). On the other hand, the Evershed flow, which is expected to follow the field lines in such a highly conducting plasma, is horizontal. This apparent contradiction can only be resolved if the field is inhomogeneous.

2.1. Fluted fields in the outer penumbra

High-resolution observations have confirmed that there are indeed large differences between the inclinations of the penumbral magnetic field in bright and dark filaments (e.g. Title et al. 1993; Lites et al. 1993; Solanki & Montavon 1993). This effect is shown dramatically in Figure 2. The inclination of the field in the bright filaments increases from about $40^\circ$ at the umbral-penumbral boundary to around $60^\circ$ at the edge of the spot, while in the dark filaments, where the field is systematically weaker, its inclination increases from $45^\circ$ to over $90^\circ$ (Langhans et al. 2005). In the outer penumbra there is therefore a difference of $30-40^\circ$ between the field directions in adjacent filaments, as shown in Figure 3. This interlocking-comb (or, better, interlocking-sheet) structure (Thomas & Weiss...
1992) – which has been variously described as uncombed, fluted, spiny or interdigitated – is further supported by results from spectropolarimetry, which require a two-component model for the field (Bellot Rubio et al. 2003; Bellot Rubio, Balthasar, & Collados 2004; Borrero et al. 2005). Furthermore, it has now been firmly established that, as expected, the Evershed flow, which is predominantly in the dark filaments, is locally parallel to the magnetic field (Bellot Rubio et al. 2004).

What is even more surprising is that the more inclined (and weaker) fields, which are more or less horizontal in the outer 20% by radius of the spot, actually plunge downwards in the outermost part of the penumbra, while the Evershed flow likewise returns below the surface either just inside or just outside the spot (e.g. Rimmele 1995; Stanchfield, Thomas & Lites 1997; Westendorp Plaza et al. 1997; Tritschler et al. 2004; Langhans et al. 2005). This configuration appears counter-intuitive, since it should be opposed both by magnetic tension along the field lines and by magnetic buoyancy.

Observations also rule out interchanges between the fields in bright and dark filaments. X-ray images (Sams, Golub, & Weiss 1992) as well as the striking images obtained by TRACE (Winebarger et al. 2001) show loops that emerge from the inner penumbra and have footpoints in an adjacent spot or even further away. There is no way that such field lines can interchange with fields that plunge below the photosphere at the edge of the spot and so it is necessary to consider families of field lines that are permanently distinct from each other, as well as from those field lines that remain above the photosphere to form a canopy (Solanki 2003). The principal (but by no means the only) challenge for theory is to provide an explanation for this interlocking magnetic structure.

2.2. Hyperfine structure in bright filaments

In the inner penumbra, near the umbra-penumbra boundary, the bright filaments alternate with dark lanes in which the magnetic field is slightly weaker. The latest high-resolution images obtained with the SST show that bright filaments typically contain dark cores that run along their lengths, extending for several thousand kilometres into the penumbra (Scharmer et al. 2002; Rouppe van der
Figure 4. Dark cores in penumbral filaments, shown up in a G-band image from the SST. (After Rouppe van der Voort et al. 2004).

Voort et al. 2004), as shown in Figure 4.\(^1\) Doppler measurements show that there is a strong outflow in the dark cores, with a velocity that is steeply inclined to the vertical (Bellot Rubio, Langhans & Schlichenmaier 2005) and a correspondingly inclined magnetic field (Langhans et al. 2005). This structure is noticeably clearer on the center-side than on the limb-side of the penumbra, implying that the cores are shallow features at the top of the bright filaments (Süttterlin, Bellot Rubio & Schlichenmaier 2004).

The inner ends of the bright filaments penetrate into the umbra, terminating in a bright point, or grain, that is more clearly visible on the limb-side of the penumbra. These bright points tend to be centered on the lateral brightenings rather than the dark cores (Süttterlin et al. 2004) and are associated with upflows (Rimmele 2004). G-band movies show that this process is time-dependent, as filaments headed by bright points penetrate into the umbra and then fade away, perhaps to reappear as a new bright point emerges and travels inwards (Scharmer et al. 2002). These changes probably correspond to motion of a pattern rather than to bodily displacements (Rouppe van der Voort et al. 2004). The lifetimes of individual bright filaments range from 20 minutes to more than one-and-a-half hours (Süttterlin et al. 2004; Langhans et al. 2005). At their outer ends they merge into the ‘fuzzy’ structure of the outer penumbra, where bright and dark features are less readily distinguished. The Evershed flow appears in both bright and dark filaments and may even link the former with the latter at different radii (Schlichenmaier, Bellot Rubio & Tritschler 2005).

\(^1\)These dark cores were already visible in images obtained with the Swedish Vacuum Solar Telescope – see Figure 7 of Thomas & Weiss (2002).
3. **Questions Raised by Observations**

It is abundantly clear that, so far as sunspots are concerned, observations lead theory. The *gross structure* of a sunspot – the distinction between its umbra and penumbra – could not be explained until the *fine structure* of the penumbral magnetic field had been established. At this stage, the immediate role of theory is to explain the underlying physics that leads to this remarkable magnetic configuration. Not until that has been achieved will it become possible for massive computation to take over and to simulate the observations in enormous detail.

Before proceeding further it may be useful to list some of the key questions raised by observations of sunspots.

- How is the interlocking-comb magnetic structure maintained?
- How does this structure originate?
- What drives the Evershed flow?
- Why is the umbra so different from the penumbra?
- What are umbral dots?
- What is the nature of convection in bright and dark penumbral filaments?
- What is the origin of hyperfine structure within filaments and light bridges?
- What is the subsurface structure of a sunspot – a tight cluster or a coherent tube?
- What radial flows exist in the moat cell?

As might be expected, scarcely any of these questions can be answered adequately at the moment.

4. **Towards a Theoretical Picture**

4.1. **Downward Pumping of Magnetic Flux**

The magnetic field in dark filaments cannot dive down below the photosphere at the edge of a sunspot unless there is some mechanism that drags it under. The only obvious effect is downward pumping of magnetic flux by the turbulent convection outside the spot. Illustrative calculations, with highly idealized models, demonstrate that this process is robust (Thomas et al. 2002; Weiss et al. 2004). It is conjectured that vigorous small-scale granular convection, with a characteristic horizontal scale of around one Mm, can keep horizontal fields submerged at a level where the relatively placid supergranular-scale circulation in the moat cell that surrounds a sunspot only affects the outward motion of vertically oriented fields. Some evidence for the existence of this process is provided by observations of the Evershed flow in \( \delta \)-spots (which are of opposite polarity and share a common penumbra). Lites et al. (2002, see Figure 11)
interpreted their observations as evidence for field lines that plunged below the surface near the polarity reversal, in a manner that is consistent with magnetic pumping. Similarly, the appearance of moving magnetic features in the moat can be explained as due to the emergence at the surface of stitches of magnetic flux that have been lifted up from a submerged flux sheet (Shine & Title 2001; Sainz Dalda & Martínez Pillet 2005).

4.2. A Convectively Driven Fluting Instability

In any pore model the inclination of the magnetic field at the magnetopause increases as the magnetic flux is increased. Although a spot configuration in an adiabatically stratified atmosphere can be stabilized against fluting instabilities by magnetic buoyancy (Meyer, Schmidt, & Weiss 1977), it is necessary to take account of convection both inside and outside the flux tube. Cellular convection is preferred when the field is vertical or only slightly inclined but as the inclination is progressively increased there is bound to be a transition to radially oriented rolls (Danielson 1961b); this explains the transition from the umbra to the penumbra in a sunspot. Similar fluting instabilities have been demonstrated in illustrative calculations (Hurlburt, Matthews, & Rucklidge 2000; Hurlburt & Alexander 2002; Tildesley 2003; Tildesley & Weiss 2004). It is conjectured that such a convectively driven instability initiates the filamentary fluting in a protospot, and that there is then a jump to a fully formed penumbra as depressed filaments are grabbed and pumped downwards by external convection (Thomas & Weiss 2004). The resulting hysteresis explains why the largest pores are bigger than the smallest spots (Rucklidge, Schmidt, & Weiss 1995).

4.3. The Evershed Flow

Measured velocities in sunspots are aligned with the magnetic field (Bellot Rubio et al. 2004). Flows along a flux tube are driven by a difference in gas pressure between the two ends, caused either by enhanced pressure at the upstream end (the piston effect) or by a pressure deficit at the downstream end (the siphon effect). The large-scale Evershed outflow in the outer penumbra is most readily explained as a siphon flow, resulting from differences in magnetic pressure on a surface of constant total pressure (Montesinos & Thomas 1997; Borrero et al. 2005; Thomas 2006). The flow along dark cores in bright filaments may, however, be driven by a pressure excess, as is the case in Schlichenmaier’s (2002) moving flux tube model.

4.4. Convection in a Sunspot

It has been known for many years that the energy radiated from the umbra or penumbra of a sunspot has to be supplied predominantly by convection. Systematic numerical investigations of three-dimensional compressible magnetoconvection have revealed several different regimes (Weiss, Proctor, & Brownjohn 2002). In the strong field regime there is only small-scale cellular convection, which may be time-dependent; with weaker imposed fields flux separation can occur, leading to patches of almost field-free convection enclosed by regions of stronger field; finally, for much weaker fields magnetic flux is confined to isolated flux elements, as in the quiet Sun. Sunspots apparently correspond to the strong field regime, for there is no sign of field-free convection at the surface.
**Umbral Dots** The umbral photosphere is stably stratified and any convective plumes have to penetrate a radiative blanket if they are to be detected. Nevertheless, recent observations concur in finding upflows and weaker fields in umbral dots (Rimmele 2004; Socas-Navarro et al. 2004). This is consistent with the behaviour of aperiodic spatially modulated oscillations in the strong field regime (Weiss et al. 1996; Hurlburt et al. 2000). In an imposed vertical field, with no preferred horizontal direction, such three-dimensional convective structures are preferred (Clune & Knobloch 1993); once the field is inclined, this symmetry is broken and the cells begin to drift, typically away from the direction of tilt (Hurlburt et al. 2000) as exemplified by the inward motion of dots and bright grains at the periphery of the umbra. The existence of dark nuclei, with smaller umbral dots, may indicate some form of flux separation within the umbra. The fact that the dots are isolated, pointlike features argues against the presence of isolated flux tubes surrounded by field-free plasma, which would give rise to a bright network.

**Penumbral Filaments** Further increases in the inclination of the imposed field lead to convection in elongated cells and, eventually, in rolls aligned with the magnetic field (Hurlburt et al. 2000; Julien, Knobloch, & Tobias 2000; Thompson 2005). The pattern of convection in the inner penumbra apparently corresponds to filamentary rolls, with alternating sheets of hot rising and cool sinking plasma and, correspondingly, minor differences in the inclinations of the magnetic field. This structure is time-dependent and any longitudinal modulation tends to travel inwards as a wavellite pattern.

The outer penumbra has a very different structure, with markedly disparate field inclinations. The less inclined fields presumably continue to support elongated rolls with modulated traveling waves, while roll-like interchanges are preferred where the field is almost horizontal. The Evershed flow is associated with the latter fields but bright and dark regions are only weakly correlated with magnetic inclination.

4.5. **Dark Cores in Filaments and Light Bridges**

Light bridges follow fissures in the umbra and high-resolution images show that they are segmented, with narrow dark cores along their lengths (Berger & Berdyugina 2003; Lites et al. 2004). It is also clear that these are elevated structures, with magnetic fields that are locally almost horizontal but compressed between the steeper fields of the neighbouring umbrae (Lites et al. 2004). These dark cores bear a close resemblance to those within bright filaments in the inner penumbra. Spruit & Scharmer (2006), quoting an unpublished calculation by Nordlund & Stein, argue convincingly that they both arise as dark absorption features produced by a thin strip of gas that has a higher pressure than its surroundings. This strip is trapped between a rising convective plume and ambient strong magnetic fields, and the same high pressure might also drive the observed flow along dark cores in bright penumbral filaments.

\[^2\]Unfortunately this neat explanation is embedded in a farrago of misconceptions.
4.6. Subsurface Structure and Surrounding Flows

Helioseismology makes it possible to probe the subsurface structure of sunspots. Measurements of $p$-mode travel times indicate that the spot persists as a coherent structure for at least ten Mm below the surface (e.g. Kosovichev 2002). Theoretical investigations of magnetoconvection imply that the corresponding magnetic field should form an inhomogeneous column rather than a tight cluster of individual tubelets. At the photosphere a well-developed sunspot is surrounded by an annular moat cell with a radial outflow that can be directly measured (Shine & Title 2001) but the helioseismic results are controversial: $f$-mode measurements show an outflow at the surface, as expected, (Gizon, Duvall, & Larsen 2001), while $p$-modes indicate an inflow, with outflows at greater depths (Kosovichev 2002). Relying on an axisymmetric numerical model, Hurlburt & Rucklidge (2000) have suggested that the inflow may be concealed beneath the spreading field in the penumbra.

5. Future Developments

The last ten to fifteen years have seen an explosion in our understanding of sunspots and there is every reason to expect this rapid progress to continue. So far as observations are concerned there will soon be improved high-resolution spectroscopic measurements on the current telescopes; within the next few years we can expect to have continuous coverage of three-dimensional magnetic fields and fine structure from the Solar-B and SDO missions; and in the longer term we can look forward to observations at much higher resolution from ATST. These observations will clarify the physical mechanisms that are involved. Theory will then be able to draw on detailed numerical models of the relevant nonlinear processes, aided by the availability of even more powerful computers (for as long as Moore’s Law holds). We must also expect some new surprises. Sunspots may be an old problem but there is a promising future ahead for the next generation of students.

Acknowledgments. I am especially grateful to Jack Thomas, as well as to Nic Brummell, Mike Tildesley, and Steve Tobias, and I have also benefitted from discussions with Thomas Rimmele, Rolf Schlichenmaier, and Alan Title. I thank the organizers for inviting me to this Workshop – and Bob Stein for providing the occasion for holding it.

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