

To appear in "Magnetic Coupling between the Interior and the Atmosphere of the Sun", eds. S. S. Hasan and R. J. Rutten, Astrophysics and Space Science Proceedings, Springer-Verlag, Heidelberg, Berlin, 2009.

Theoretical Models of Sunspot Structure and Dynamics

J. H. Thomas

Department of Mechanical Engineering and Department of Physics & Astronomy,
University of Rochester, USA

Summary. Recent progress in theoretical modeling of a sunspot is reviewed. The observed properties of umbral dots are well reproduced by realistic simulations of magnetoconvection in a vertical, monolithic magnetic field. To understand the penumbra, it is useful to distinguish between the inner penumbra, dominated by bright filaments containing slender dark cores, and the outer penumbra, made up of dark and bright filaments of comparable width with corresponding magnetic fields differing in inclination by some 30 degrees and strong Evershed flows in the dark filaments along nearly horizontal or downward-plunging magnetic fields. The role of magnetic flux pumping in submerging magnetic flux in the outer penumbra is examined through numerical experiments, and different geometric models of the penumbral magnetic field are discussed in the light of high-resolution observations. Recent, realistic numerical MHD simulations of an entire sunspot have succeeded in reproducing the salient features of the convective pattern in the umbra and the inner penumbra. The siphon-flow mechanism still provides the best explanation of the Evershed flow, particularly in the outer penumbra where it often consists of cool, supersonic downflows.

1 Introduction

Understanding the structure and dynamics of a sunspot poses a formidable challenge to magnetohydrodynamic theory. The marvelous details revealed in high-resolution observations of sunspots have shown how very complex a sunspot is, but have also stimulated real progress in theoretical modeling.

Here I review recent advances on some important theoretical issues concerning sunspots, including the following questions. Is the overall near-surface structure of a sunspot best described as a monolithic (but inhomogeneous) magnetic flux tube or as a cluster of individual flux tubes? What is the nature of magnetoconvection in a sunspot, and how does it produce the umbral dots and the filamentary intensity pattern in the penumbra? What causes the complicated interlocking-comb configuration of the magnetic field in the penumbra? How do we explain the significant differences between the inner

and outer penumbra? What causes the Evershed flow in the penumbra? How do the outflows along the dark penumbral cores in bright filaments in the inner penumbra relate to the stronger and downward plunging Evershed flows in the outer penumbra?

This review is of necessity selective, and some important topics will not be discussed at all (for example, sunspot seismology, which is well covered by Rajaguru and Hanasoge in this volume). For a broader coverage of both theory and observations of sunspots, see the recent book by Thomas & Weiss (2008) and the reviews by Solanki (2003) and Thomas & Weiss (2004).

2 Umbral magnetoconvection

In a broad sense, there are two competing models of the structure of a sunspot below the solar surface: a monolithic, but inhomogeneous, magnetic flux tube, or a tight cluster of smaller flux tubes separated by field-free plasma (Parker 1979). One way in which we might distinguish between these two models is to examine the form of convective energy transport in the umbra, and in particular the mechanism that produces the bright umbral dots.

In the monolithic model, the umbral dots are thought to correspond to slender, hot, rising plumes that form within the ambient magnetic field and penetrate into the stable surface layer, spreading horizontally and sweeping magnetic flux aside (flux expulsion), thereby producing a small, bright region with a weakened magnetic field. This picture is supported by several idealized model calculations involving both Boussinesq and fully compressible magnetoconvection (see the reviews by Proctor 2005 and Thomas & Weiss 2008). In the cluster model, convection is imagined to be effectively suppressed in the magnetic flux tubes but unimpeded in the nearly field-free regions around them, where the convection penetrates upward into the visible layers to form bright regions. In that case, however, we might reasonably expect to see a bright network enclosing dark features, rather than the observed pattern of bright, isolated umbral dots on a dark background (e.g., Knobloch & Weiss 1984). The essential differences between the monolith and cluster models are that in the cluster model the weak-field gaps are permanent and are connected to the field-free plasma surrounding the sunspot, whereas in the monolithic model the gaps are temporary and are embedded within the overall flux tube, isolated from the surroundings of the spot.

Recently, Schüssler & Vögler (2006) carried out realistic numerical simulations of umbral magnetoconvection in the context of the monolithic model, assuming an initially uniform vertical magnetic field. They study three-dimensional compressible magnetoconvection within a realistic representation of an umbral atmosphere, including partial ionization effects and radiative transfer. Their model reproduces all of the principal observed features of umbral dots (see, e.g., Bharti, Jain & Jaaffrey 2007). The results show an irregular pattern of slender, isolated plumes of width 200–300 km and lifetime

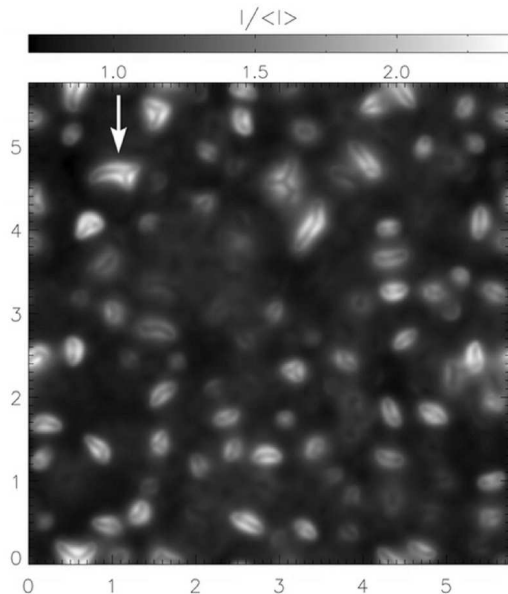


Fig. 1. The pattern of vertically emerging surface intensity in a realistic numerical simulation of umbral magnetoconvection. (From Schüssler & Vögler 2006.)

around 30 min. An individual plume achieves a peak upward velocity of about 3 km s^{-1} before decelerating (by buoyancy braking) and spreading laterally as it meets the stable surface layer, greatly reducing the local magnetic field strength. Figure 1 shows a snapshot of the emerging intensity at the surface corresponding to optical depth $\tau_{500} = 1$ (which is elevated above the rising plumes). Note that the plumes are generally oval rather than circular in shape, and they have dark streaks along their major axes. These dark streaks are absorption features caused by the local increase of density and pressure associated with buoyancy braking of the plumes (cf. Section 6). The dark streaks have been seen in Hinode observations (Bharti et al. 2009).

While the results of Schüssler & Vögler do not necessarily rule out the cluster model, they do provide strong support for the monolithic model, in the sense that they show that umbral dots arise naturally as a consequence of magnetoconvection in a space-filling, vertical magnetic field. The magnetic flux is partially expelled from the plume regions to allow convective motions to occur, but these regions are not entirely field free and, more importantly, they are isolated within the overall flux bundle and not in contact with field-free plasma below, as they would be in the cluster model.

3 The inner and outer penumbra

In understanding the structure of the penumbra, it is useful to distinguish between the *inner* and the *outer* penumbra (Brummell et al. 2008). The bound-

ary between them is somewhat arbitrary, but it may be conveniently defined as the line separating inward-moving and outward-moving grains in the bright filaments, lying at about 60% of the radial distance between the inner and outer edges of the penumbra and dividing the penumbra into roughly equal surface areas (Sobotka, Brandt & Simon 1999; Sobotka & Sütterlin 2001; Márquez, Sánchez Almeida & Bonet 2006). This pattern may be understood as a transition from isolated, vertical convective plumes in the umbra to elongated, roll-like convective structures in the outer penumbra, as a consequence of the increasing inclination (to the local vertical) of the magnetic field. The moving bright grains are then traveling patterns of magnetoconvection in an inclined magnetic field, with the motion switching from inward to outward at some critical inclination angle of the magnetic field.

The inner penumbra is dominated by bright filaments containing slender dark cores (Scharmer et al. 2002; Langhans et al. 2007) and has relatively small azimuthal variations in the inclination of the magnetic field. The field in a dark core is slightly more inclined than the field in its bright surroundings, by some 4–10°. A dark core typically originates at a bright feature near the umbra, where there is an upflow that bends over into an outflow along the inclined magnetic field in the core.

The outer penumbra, on the other hand, is made up of dark and bright filaments of comparable width, with corresponding magnetic fields differing significantly in inclination, by 20–30° or more, the more horizontal field being in the dark filaments. The Evershed flow is stronger in the outer penumbra and is generally concentrated in the dark filaments, along nearly horizontal and often downward-plunging magnetic fields, with the flow velocity and the magnetic field well aligned all along the filament. One of the most intriguing features of the outer penumbra is the presence of “returning” magnetic flux, that is, field lines with inclinations greater than 90° that plunge back below the solar surface. There is now overwhelming observational evidence for a substantial amount of returning magnetic flux in the outer penumbra, in several high-resolution polarimetric studies based on different inversion schemes (e.g., Westendorp Plaza et al. 2001; Bellot Rubio, Balthasar & Collados 2004; Borrero et al. 2004; Langhans et al. 2005; Ichimoto et al. 2007, 2009; Beck 2008; Jurčák & Bellot Rubio 2008).

The outer edge of the penumbra is quite ragged, with prominent dark filaments protruding into the surrounding granulation. The proper motions of granules in the moat surrounding a spot show convergence along radial lines extending outward from the protruding dark filaments (Hagenaar & Shine 2005), providing evidence for submerged magnetic flux extending outward from the spot. This submerged magnetic field is presumably held down, in opposition to its inherent buoyancy, by magnetic flux pumping, as described in the next section.

4 The formation and maintenance of the penumbra

One of the important challenges for sunspot theory is to explain how the filamentary penumbra forms and its magnetic field acquires the observed interlocking comb structure with downward-plunging field lines in the outer penumbra, and how this structure is maintained. Eventually this whole process may be amenable to direct numerical simulation (see Section 6 below), but for now we can only speculate based on less ambitious models of specific aspects of the process.

The following scenario has been suggested for the formation of a fully fledged sunspot with a penumbra (Thomas et al. 2002; Weiss et al. 2004). The development of a solar active region begins with the emergence of a fragmented magnetic flux tube into the photosphere. The emergent flux is quickly concentrated into small, intense magnetic elements which can accumulate in the lanes between granules and mesogranules to form small pores. Some of these pores and magnetic elements may then coalesce to form a sunspot. Simple models show that, as a growing pore accumulates more magnetic flux, the inclination (to the local vertical) of the magnetic field at its outer boundary increases until it reaches a critical value, whereupon a convectively driven fluting instability sets in and a penumbra forms. The fluting of the magnetic field near the outer boundary of the sunspot’s flux tube brings the more horizontal spokes of field into greater contact with the granulation layer in the surroundings, and then downward magnetic pumping of this flux by the granular convection further depresses this magnetic field to form the “returning” magnetic fields (inclination greater than 90°) seen in the outer penumbra. The transition between a pore and a sunspot shows hysteresis, in the sense that the largest pores are bigger than the smallest sunspots; this may be explained by the flux-pumping mechanism, which can keep the fields in the dark filaments submerged even when the total flux in a decaying spot is less than that at which the transition from pore to spot occurred.

We have demonstrated the efficacy of the process of magnetic flux pumping by granular convection through a series of idealized numerical experiments (Thomas et al. 2002; Weiss et al. 2004), most recently for a more realistic, arched magnetic field configuration that accounts more accurately for the magnetic curvature forces (in addition to the buoyancy forces) opposing the downward pumping (Brummell et al. 2008). We solve the equations governing three dimensional, fully compressible, nonlinear magnetoconvection in a rectangular box, consisting of two layers: an upper, superadiabatic layer of vigorous convection representing the granulation layer, and a lower, marginally stable or weakly superadiabatic layer representing the rest of the convection zone. The simulation is run without a magnetic field until a statistically steady state is reached, and then a strong magnetic field is introduced, in the form of a purely poloidal (x - z), double arched magnetic field, and the gas density is adjusted to maintain pressure equilibrium. The calculation proceeds and we examine the effect of the convection in redistributing the magnetic flux.

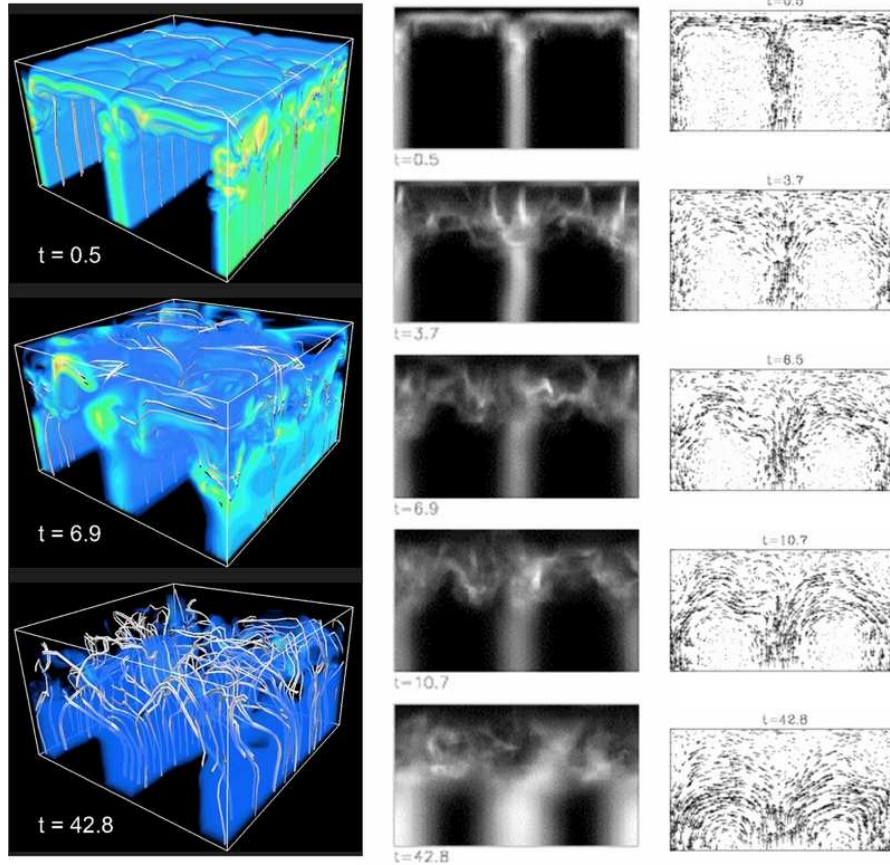


Fig. 2. Numerical simulation of downward magnetic flux pumping of penumbral magnetic fields by granular convection in the surroundings. The panels show volume renderings of magnetic energy density (left), x -averaged magnetic energy density (middle), and the x -averaged vector magnetic field at different times during the run. (Here x is the direction perpendicular to the page.) The initial arched magnetic field configuration is still distinctly visible in the uppermost plots at $t = 0.5$. (From Brummell et al. 2008.)

Figure 2 shows the state of the magnetic field shortly after it was introduced (scaled time $t = 0.5$) and at a few later stages, the last stage ($t = 42.8$) being after a new quasi-steady statistical state has been reached. Here we see that a significant fraction of the large-scale magnetic field is pumped rapidly downward out of the upper granulation layer and concentrated mostly in the upper part of the lower, more quiescent convective layer. These new numerical experiments demonstrate that the downward pumping by turbulent granular convection is indeed able to overcome the combined effects of the magnetic buoyancy force and the curvature force due to magnetic tension, and thus

to submerge much of the initial, nearly horizontal magnetic flux beneath the granulation layer, as we propose in the scenario presented above.

5 The magnetic field configuration in the penumbra

Here we consider some geometric models that have been proposed for the observed interlocking-comb structure of the penumbral magnetic field. The scenario described in Section 4 for the formation of the penumbra and the returning flux tubes through flux pumping leads us to a magnetic field configuration in the outer penumbra roughly as depicted in the right-hand panel of Figure 3 (Thomas et al. 2006; Brummell et al. 2008). This configuration, which we might describe as an “interleaved sheet” model, has vertical sheets of nearly horizontal magnetic field (dark filaments) interleaved between sheets of more vertical magnetic field (bright filaments). In this picture, the sheets of horizontal field extend downward below the visible surface to a depth of, say, 5 Mm. (A simple estimate gives the depth of penetration equal to one-quarter of the width of the penumbra: Brummell et al. 2008).

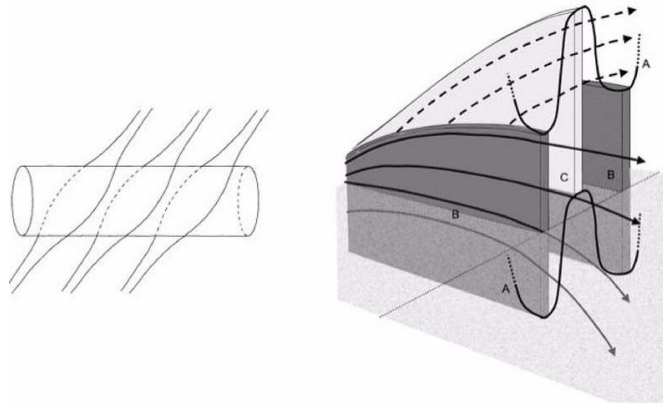


Fig. 3. Two simple models of the penumbral magnetic field configuration. Left panel: Sketch of the magnetic field configuration in the “uncombed” penumbral model of Solanki & Montavon (1993), with an ambient magnetic field wrapping around a thin horizontal flux tube (dark filament). Right panel: Schematic diagram of the “interleaved sheet” model of the outer penumbra (Brummell et al. 2008.), with a fluted magnetopause (A) and slabs of nearly horizontal magnetic field (B, dark filaments) extending downward to some depth below the surface and separated by a slab of less steeply inclined magnetic field (C, bright filament).

Another geometric model, with a longer history, is the “uncombed” penumbral model¹ of Solanki & Montavon (1993), depicted in the left-hand panel of Figure 3. In this model the more horizontal component of the penumbral magnetic field is represented by horizontal magnetic flux tubes, of nearly circular cross-section, embedded in a more vertical background magnetic field that wraps around these tubes. Scharmer & Spruit (2006) pointed out that the magnetic tension forces in the background magnetic field will tend to compress a circular flux tube in the horizontal direction, causing it to expand upward at the top and downward at the bottom, perhaps indefinitely. Borrero, Rempel & Solanki (2006) then argued that buoyancy forces will halt this squeezing process, leaving a flux tube of tall, narrow cross-section. If the vertical elongation of the flux tube is significant, the configuration begins to look much like the interleaved sheet model depicted in the right-hand panel of Figure 3, and these two models are then not very different.

A quite different model of the penumbral magnetic field, the “gappy penumbra” model of Spruit & Scharmer (2006; Scharmer & Spruit 2006), is based on the cluster model of a sunspot. It postulates field-free, radially aligned gaps in the magnetic field below the visible surface of the penumbra, protruding into a potential magnetic field configuration. The gaps are assumed to extend indefinitely downward, allowing the field-free convection in the gaps to carry the bulk of the upward heat flux in the penumbra. Figure 4 shows the proposed magnetic field configuration. The gaps themselves represent the bright penumbral filaments, while the intervening regions of strong magnetic field represent the dark filaments. As can be seen from the contours of constant inclination in Figure 4, the magnetic field is more nearly horizontal above the bright filaments (the gaps) and more nearly vertical (here 45°) above the dark filaments. However, this magnetic field configuration is in direct contradiction with numerous observations that show that the field is more horizontal in the dark filaments (e.g., Rimmele 1995; Stanchfield, Thomas & Lites 1997; Westendorp Plaza et al. 2001; Langhans et al. 2005), including very recent spectropolarimetric observations from Hinode by Jurčák & Bellot Rubio (2008) and by Borrero & Solanki (2008). The last authors also examined the vertical stratification of magnetic field strength in the penumbra and found that it is inconsistent with the existence of regions void of magnetic field at or just below the $\tau_{500} = 1$ level. While the gappy penumbra model itself contains no flows, Spruit & Scharmer suggest that the Evershed flow occurs along the (very restricted) region of nearly horizontal field just above the center of the gap. At least in the outer penumbra, this is in conflict with numerous observations that show that the flow is concentrated in the dark filaments. It seems, then, that the gappy penumbra is incompatible with observations.

¹ Sometimes the term “uncombed” is used more generally to describe the observed penumbral field configuration, but here I use the term specifically to represent the geometric model proposed by Solanki & Montavon (1993).

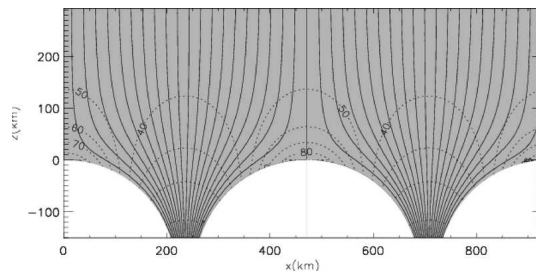


Fig. 4. The potential magnetic field configuration in the “gappy penumbra” model of Spruit & Scharmer (2006). Shown here are the magnetic field lines (solid lines) projected onto a vertical (x - z) plane perpendicular the axis (y -axis) of a penumbral filament, along with contours (dotted lines) of constant inclination of the field in the y - z plane.

Spruit & Scharmer (2006) also suggested that the observed narrow dark cores running along the center of bright filaments in the inner penumbra can be understood as an effect of the increased opacity due to increased gas pressure in the field-free gaps. This important suggestion seems to be basically correct, although the field-free gaps are not necessary: dark cores also form as opacity effects in the case of magnetoconvection in a strong-field region, as shown in the simulations of umbral dots discussed in Section 2 above and in the simulations of penumbral filaments discussed in the next section.

6 Numerical simulations of a sunspot

Any attempt to perform a direct numerical MHD simulation of an entire sunspot faces serious computational difficulties: the simulation must represent a very large structure while still resolving fine-scale features and even smaller scale diffusive effects; it must cope with a wide range of values of the Alfvén speed and plasma beta; and the computation must be carried out long enough to reach a relaxed, quasi-steady state. In spite of these formidable problems, there have been very recently impressive attempts by two groups to model an entire sunspot by direct, realistic simulations including radiative transfer (Heinemann, Nordlund, Scharmer & Spruit 2007; Rempel, Schüssler & Knölker 2009). These efforts are surely just the beginning of a new and fruitful approach to sunspot theory.

Both groups model a large section of a sunspot in a rectangular box. They each introduce a two-dimensional, vertically spreading, initial magnetic field into a state of fully developed nonmagnetic convection representing the upper convection zone and a stable atmospheric layer above it. The calculations continue for several hours of real (solar) time, through a dynamic adjustment phase, until a quasi-steady state is attained. The results show the formation

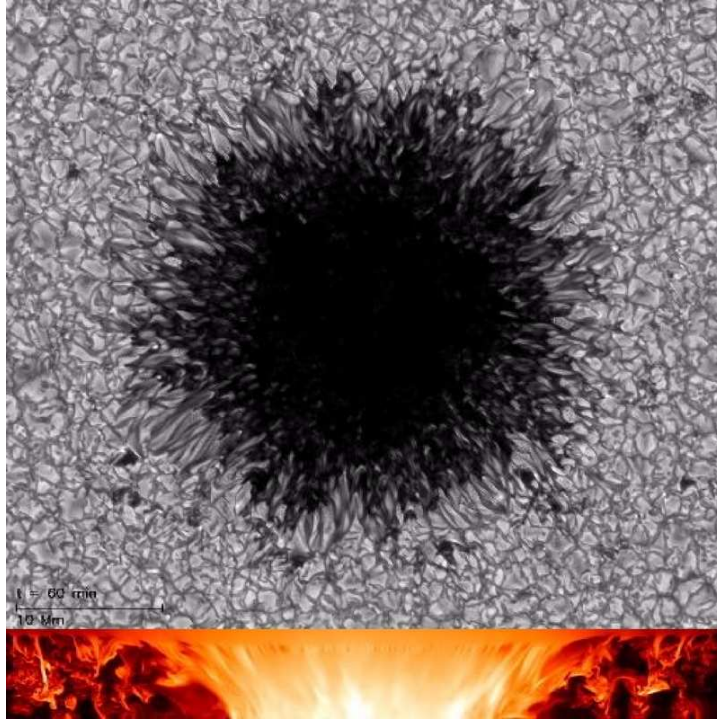


Fig. 5. Numerical simulation of a circular sunspot, following the same method as in the slab model of Rempel et al. (2009). Shown here are (above) a snapshot of the surface intensity and (below) the corresponding values of $|B|^{1/2}$ on a vertical slice through the center of the spot, depicted on a color scale. (Courtesy of Matthias Rempel.)

of filamentary structures resembling those in the inner penumbra of a real sunspot, including bright filaments containing central dark cores.

In very recent work, Rempel et al. have extended their simulations to model an entire circular sunspot within a rectangular box. Figure 5 shows a snapshot of the surface intensity pattern and magnetic field in this beautiful simulation.

The simulations reproduce most of the important features of the bright penumbral filaments found in the inner penumbra. Figure 6 shows a blowup of a single bright penumbral filament produced in the rectangular sunspot simulation of Rempel et al. (2009). The continuum intensity pattern shows an elongated bright filament with a dark central core and a bright “head”, which migrates inward toward the umbra during the lifetime of the filament. The dark core is produced as an opacity effect due to buoyancy braking of the upflow, much as in the simulations of umbral dots discussed in Section 2. The

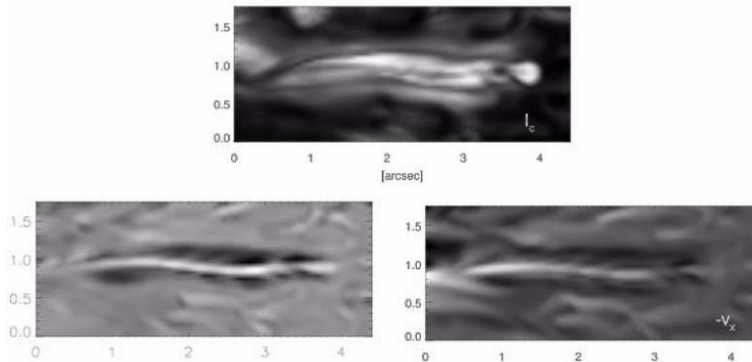


Fig. 6. Enlarged view of a single bright penumbral filament produced in the simulation of Rempel et al. (2009). The umbra lies to the right of this filament. The upper panel shows a surface continuum intensity image at wavelength 630 nm, and the lower panels show vertical velocity v_z (left) and horizontal velocity v_x (right), where the x -axis is parallel to the bottom of the panels.

magnetic field (not shown here) is weaker and more inclined in the filament than in its immediate surroundings.

The pattern of vertical velocity shows roll-like convection along the filament with an inclined upflow along the central axis of the filament (i.e., along the dark core) and inclined downflows (return flows) along the sides of the filament. Correspondingly, the radial (x) component of the velocity is outward along the axis of the filament, with a peak value of about 2 km s^{-1} , and inward along the sides of the filament. The return flow is in regions with stronger and less inclined magnetic field, so the horizontal component is smaller in magnitude than that in the outflow at the same optical depth; as a result, the radial inflows and outflows do not cancel when averaged in the y -direction, but instead show an average outflow of about 1 km s^{-1} .

The simulated penumbral filaments are slender structures with a width of a few hundred km and a depth of about 2 Mm. The filaments form and remain embedded within an overall region of strong magnetic field, and they are well isolated from the field-free convection beneath the penumbra. As Rempel et al. emphasize, these weak-field “gaps” formed within the overall magnetic field by the convection are fundamentally different from those proposed in the “gappy penumbra” model of Spruit & Scharmer, which are protrusions of the exterior field-free plasma into the penumbra as envisioned in the cluster model (see Section 5). At a fundamental level, the simulations discussed in this section are based on the monolithic model and they support that model by producing results that match observations of the inner penumbra; they lend no support for the “gappy penumbra”.

Rempel et al. also point out that their results do not support the “moving tube” model of Schlichenmaier, Jahn & Schmidt (1998): vertical heat trans-

port takes place all along the simulated filaments, not just along separate, thin flux tubes, and the movement of the filament “heads” inward toward the penumbra is due to a propagation of the magnetoconvective pattern rather than the bodily motion of an individual thin flux tube.

In both simulations discussed above, the overall extension of the penumbra is rather small and the inclination of the magnetic field in the outer part of the penumbra is generally much less than that found in a real sunspot. Thus, as both groups admit, the simulations so far seem to reproduce only the inner penumbra. One reason for this is that the periodic boundary conditions employed effectively place another sunspot of the same magnetic polarity nearby, on either side of the simulated spot. This hinders the formation of nearly horizontal fields in the outer penumbra. (Indeed, observations show that sunspots often do not form a penumbra in a sector near another spot of the same polarity.) This could be remedied, for example, by using periodic boundary conditions like those of Brummell et al. (2008), which produce a row of spots of alternating polarity (see Fig. 2).

7 The Evershed flow

Since the occasion for this meeting is the centennial of John Evershed’s discovery, it seems appropriate to close with some remarks about theoretical interpretations of the Evershed flow. The flow occurs along arched, elevated flow channels. Recent results from Hinode support this picture. Ichimoto et al. (2007) find that the Evershed downflows in the outer penumbra have the flow velocity vector and magnetic field vector well aligned, at an angle of about 30° to the solar surface. Jurčák & Bellot Rubio (2008) find that the average inclination of the magnetic field associated with the Evershed flow channels increases from 85° to 105° in going from the middle to the outer penumbra, quite consistent with the earlier results of Langhans et al. (2005) from the Swedish Solar Telescope.

The arched nature of the flow channels and the strong, often supersonic, field-aligned downflows in the outer penumbra are well reproduced in the siphon flow model (e.g., Montesinos & Thomas 1997). The “moving tube” model of Schlichenmaier, Jahn & Schmidt (1998) does not produce this configuration: it has no returning flux or downflow, but instead has all of the flow continuing radially outward along the elevated magnetic canopy. Schlichenmaier (2002) did find a class of super-Alfvénic, serpentine solutions for his model, which do have downflows along a returning flux tube, but these flows are unphysical: the very high flow speeds are an artifact of the outer boundary condition, and moreover the flow configuration itself is gravitationally unstable (Thomas 2005) and hence will not occur. (This instability seems to have been ignored by some, however, and the serpentine solutions continue to be invoked as a possible explanation of the Evershed flow: e.g., Schlichenmaier, Müller & Beck 2007; Sainz Dalda & Bellot Rubio 2008.)

The numerical simulations discussed in the previous section produce an outward horizontal velocity component of $1\text{--}2\text{ km s}^{-1}$ along the axis of a filament (see Fig. 6), which might explain the radial outflows seen in the dark cores in the inner penumbra, although it is not clear why the associated inflows along the sides of the core are not observed. However, the simulations do not offer a complete explanation of the Evershed flow, as claimed by Scharmer, Nordlund & Heinemann (2008). In the simulations, the peak outward velocity is only about 2 km s^{-1} and the outward speed averaged over a few filaments is only about 1 km s^{-1} , considerably less than what is observed in the outer penumbra. The simulations do not come close to producing the supersonic flow speeds of $7\text{--}16\text{ km s}^{-1}$, aligned with downward-plunging returning flux tubes, that are observed in dark filaments in the outer penumbra (e.g., Westendorp Plaza et al. 2001; del Toro Iniesta, Bellot Rubio & Collados 2001; Penn et al. 2003).

The supersonic, cool Evershed downflows are an inherent feature of the siphon-flow model (Montesinos & Thomas 1997). Siphon flows still provide the best description of the Evershed flows in the outer penumbra, although the flows computed so far have all been steady state and thus do not reproduce the transient nature of flows. A thin-flux-tube model combining the best features of the siphon-flow model (arched, returning flux tubes, cool supersonic downflows) and the moving-tube model (transient flows, heating at the inner footpoint) would likely reproduce all of the salient features of the Evershed flow.

In a broad sense the Evershed flow must fundamentally be a convective phenomenon. Even in the models based on thin flux tubes – the moving tube model or the siphon-flow model – the flow is driven by a pressure difference along the tube produced by some combination of local heating (producing an increase in gas pressure) or convective collapse (producing a decrease in gas pressure), and the returning flux is produced by turbulent convective pumping. As computing capabilities increase and the numerical simulations succeed in resolving all aspects of the convection in a sunspot and its immediate surroundings, we can expect the Evershed flow and the returning flux tubes to be a natural outcome.

8 Conclusions

The principal conclusions of this review are the following:

- The observed properties of umbral dots are well explained by realistic simulations of magnetoconvection in a vertical, monolithic magnetic field; there is no need to invoke a cluster model.
- There are significant differences between the inner and outer penumbra, and it is useful to distinguish between them.

- Downward pumping of magnetic flux by turbulent granular convection offers a plausible mechanism for producing the returning magnetic flux in the outer penumbra.
- The “uncombed” and “interleaved sheet” models of the penumbral magnetic field configuration are actually quite similar, in view of the squeezing effect on the circular flux tubes in the uncombed model.
- The “gappy penumbra” model for the penumbral magnetic field configuration is not in accord with observations.
- Recent realistic simulations of an entire sunspot have succeeded in reproducing the structure of the inner penumbra. However, they do not reproduce the structure of the outer penumbra, with its horizontal and returning magnetic fields and fast (supersonic) Evershed flows along arched channels.
- Bright penumbral filaments in the inner penumbra are well reproduced in these simulations, as roll-like convection (not interchange convection). Magnetic flux is partially expelled by the convective plumes, but the resulting “gaps” are not in contact with the exterior plasma and hence are fundamentally different from the gaps in the “gappy penumbra” model. The simulations reproduce the central dark cores in the bright filaments, as an opacity effect due to buoyancy braking of the plumes, and the outflows seen in these cores.
- The siphon-flow model still provides the best description of the Evershed flow in the outer penumbra. The moving-tube model describes the transient nature of the Evershed flow but fails to produce returning flux tubes and downflows. A thin-flux-tube model combining the best features of these two models is suggested.

Acknowledgement. I thank Siraj Hasan for making it possible for me to attend this meeting, and Matthias Rempel for providing results and figures prior to their publication. I also thank my collaborators Nic Brummell, Steve Tobias, and Nigel Weiss, with special thanks to Nigel Weiss for many discussions of the topics and issues covered in this review.

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