CONVECTION AND THE ORIGIN OF EVERSHED FLOWS IN SUNSPOT PENUMBRAE

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ABSTRACT

We discuss a numerical 3D radiation-MHD simulation of penumbral fine structure in a small sunspot. This simulation shows the development of short filamentary structures with horizontal flows, similar to observed Evershed flows, and an inward propagation of these structures at a speed compatible with observations. Although the lengths of these filaments are much shorter than observed, we conjecture that this simulation qualitatively reproduces the mechanisms responsible for filament formation and Evershed flows in penumbrae. We conclude that the Evershed flow represents the horizontal-flow component of overturning convection in gaps with strongly reduced field strength. The top of the flow is always directed outward—away from the umbra—because of the broken symmetry due to the inclined magnetic field. Upflows occur in the inner parts of the gaps and most of the gas turns over radially (outward and sideways), and descends back down again. The ascending, cooling, and overturning flow tends to bend magnetic field lines down, forcing a weakening of the field that makes it easier for gas located in an adjacent layer—farther in—to initiate a similar sequence of motion, aided by lateral heating, thus causing the inward propagation of the filament.

Subject headings: magnetic fields — sunspots

1. INTRODUCTION

Only a convective process close to the visible surface can explain the substantial radiative heat flux of sunspot penumbrae. But spectroscopic studies, starting with Evershed (1909), show that penumbral flows are predominantly horizontal and increase in strength toward the outer penumbra. This gradually led to the view that Evershed flows have an origin that is unrelated to convective processes beneath the surface.

Some of the models that have been proposed to explain Evershed flows rely on the concept of nearly horizontal flux tubes, embedded in a more vertical magnetic field, and with a (siphon like) flow driven along the flux tube by enhanced gas pressure at one end of its ends (e.g., Schlichenmaier 2002). Such “siphon flow” models were first proposed by Meyer & Schmidt (1968) and were further developed by, e.g., Thomas (1988) and Thomas & Montesinos (1991). Schlichenmaier et al. (1998a, 1998b) and Schlichenmaier (2002), using 1D MHD simulations, modeled time-dependent flows in thin flux tubes embedded in an atmosphere of given properties. However, nearly horizontal flux tubes cannot carry the heat flux needed to explain the radiative losses of the penumbra (Schlichenmaier & Solanki 2003).

A different view of penumbral fine structure emerged from the discovery that bright penumbral filaments have dark cores (Scharmer et al. 2002). These dark cores were proposed by Spruit & Scharmer (2006) to be a consequence of locally enhanced gas pressure associated with the gaps combined with an overall drop of temperature with height. Within the gaps, overturning convection transports energy to the surface, providing an explanation for the penumbral heat flux. This “gappy” model explains the strongly inclined field at the locations of the dark cores as a natural consequence of a near-potential magnetic field folding over the gap. Magnetostatic models of this type are able to explain observed differences between the inner and outer penumbra (Scharmer & Spruit 2006).

Recently, Heinemann et al. (2007) presented the first 3D MHD simulations relevant to the formation of penumbral fine structure. The simulations show the formation of short filamentary structures. These filaments reproduce morphological, dynamic, and evolutionary properties that agree reasonably well with observations. We conjecture that the simulations capture the essential physics of such filaments, even though their lengths are much shorter than observed.

In the current Letter we use these simulations to make inferences about the nature of convection and Evershed flows in sunspot penumbrae. One of the main conclusions is that the Evershed flow represents the horizontal flow component of overturning convection in penumbrae.

2. MHD SIMULATIONS

The simulations of Heinemann et al. (2007) were carried out using the PENCIL code, modified to handle energy transfer by radiation in a gray atmosphere (Heinemann 2006; Heinemann et al. 2006). We used a rectangular computational box $12,448 \times 6212$ km$^2$ in the horizontal ($x$ and $y$) directions, extending over a depth ($z$) range of 3094 km and with a grid separation of 24.36 km in both horizontal and vertical directions ($512 \times 256 \times 128$ grid points). The quiet-Sun photosphere is located approximately 700 km below the upper boundary.

We emphasize the following agreement between the simulations and observed properties of penumbral filaments: (1) The association of dark cores with locally reduced field strength and a more inclined magnetic field. (2) The presence of outward horizontal flows in a thin layer close to the visible surface. (3)
The presence of strong upflows at the innermost point of the filamentary structures. (4) The inward migration of these structures toward the umbra.

2.1. Relation to Umbral Convection Simulation

The penumbra simulations show similarities with the umbral convection simulations of Schüssler & Vogler (2006). Their simulations demonstrate the development of narrow upflow plumes which become nearly field-free near the surface layers, and horizontal flows cospatial with dark lanes, similar to the dark cores seen in our simulations. Convective downflows are concentrated at the endpoints of the dark lanes, which sometimes split into Y shapes. Notably, the gaps in the umbra simulations do not extend to the bottom of the simulation box but are limited to a depth of about 500 km below the surface. The gaps formed in the penumbra simulations are similar, but aligned with an inclined field. The associated horizontal flows are always in the direction of the surrounding field-free photosphere.

The Y-shaped dark lanes seen in umbral dots in Schüssler & Vogler’s simulations are similar to observed peripheral umbral dots connected to dark-cored penumbral filaments (Langerhans et al. 2007). Recently, dark lanes in umbral fine structure have also been reported by Bharti et al. (2007) and Rimmele (2008). There is thus already observational support for these simulations, but the flows along dark lanes and downflows at their ends in the umbral dot simulations have not yet been observed.

2.2. Relation to Light Bridge Simulations

Simulations of light bridges by Nordlund (2006) and Heinemann (2006) share some crucial properties with the umbral dot simulations. The brightness is supported by convective heat transport, which here is able to push open and maintain a “gap” with strongly reduced magnetic field strength. The cusp-shaped magnetic field arching over the gap, which extends for a considerable distance, is associated with a dark core along its symmetry line. Such light bridge dark cores that continue as penumbral dark cores have been observed (Scharmer et al. 2007), suggesting a common origin.

3. Penumbra Convection and Evershed Flows

From field-free (photospheric) convection simulations (e.g., Stein & Nordlund 1998) we can estimate that hot gas needs to reach the visible surface with a vertical speed of the order of 1–2 km s$^{-1}$ in order to support and maintain the observed average luminosity of penumbras. Strong such upflows have not yet been observed in penumbras, except at the innermost parts of filaments (Rimmele & Marino 2006). The simulations demonstrate, as expected, that upflows occur in the inner parts of the gaps and downflows at their sides. The small azimuthal separations between the upflows and downflows would make such flows difficult to observe, except at their innermost parts where there are no downflows.

In the quiet Sun, convection is associated with horizontal flows that are typically twice as strong as the vertical flows and occasionally reach supersonic velocities near the photosphere (Stein & Nordlund 1998). The analogous structure of the convective flows that we observe in the penumbral simulations prompt us to identify the observed Evershed flows in the horizontal-flow component of overturning convection in penumbras. Their visibility is then clearly due to their unidirectional nature—they are always directed away from the umbra. In the simulations, the horizontal outward flows in the optically visible parts of the gaps increase toward $r = 1$, which is also where the efficiency of radiative cooling peaks. It seems well established that the Evershed flow speed increases with optical depth (e.g., Bellot Rubio et al. 2006), so the simulation results are consistent with observations also in this respect.

3.1. Convective Flows and Magnetic Field Interaction

Figure 1 shows a detail of a snapshot from the penumbra simulation of Heinemann et al. (2007). The flow field and the magnetic field are visualized in a small box centered on one of the inward-propagating penumbral filaments (the umbra is situated to the left of the box).

In the foreground one can see that the magnetic field is bent down, resulting in a locally increased inclination, and also in a local weakening of the field strength (encoded as more reddish color). The cause of this effect can be appreciated by considering the shape of the velocity field, which is illustrated in the bottom panel of the figure. As shown by the purple color, the strongest velocity field occurs to the left, at the inward-propagating head of the filament. As required by conservation of mass the ascending flow forces an overturning motion, which pushes the magnetic field aside and forces field lines to bend over outward (the cutting plane shows yellow/orange weaker vertical field).

Since these flows occur on a scale not much larger than the numerical resolution of the simulation the magnetic diffusivity is significant, and the magnetic field lines are thus able to partly slip through the flow, back toward their initial arrangement. Nevertheless, the effect of the flow on the magnetic field lines is obvious enough, and would only become stronger with decreasing magnetic diffusivity. In the limit of very small mag-
netic diffusivity one would expect that the flow would force open a nearly field-free narrow channel, with overturning convection inside. The flow pattern within such a channel would be quite similar to the flow pattern illustrated in Figure 1; the velocity field must be similar in shape and amplitude to be able to transport the necessary amount of energy up to the visible surface.

Given the necessity of horizontal flows inside the channels, and given the necessity to expose the hot gas to the surface cooling for a sufficiently long time for it to lose buoyancy and start to descend, it is clear that flows that extend along the channels (and hence also more or less along the magnetic field) are energetically as well as topologically favorable. So, while there is also a flow component across filaments, away from the center of the filament and with cooler downflows occurring near the boundaries of the gaps, the main flow direction must be along the filament.

Another way of seeing this is to consider the pressure pattern associated with the flow. The horizontal flow is primarily driven by the pressure difference between the upflow and downflow points. That pressure difference is, in turn, a consequence of the cooling that occurs as the gas reaches the surface and flows between the points of ascent and descent.

An important consequence of the surface cooling is that the gas becomes denser and heavier, and that it therefore more efficiently bends the field lines downward. This creates near-horizontal field lines that in turn can more easily accommodate horizontal flows. That tendency is clearly seen already in the current simulation, and must be even stronger in the real penumbra. Most likely this effect contributes to the “uncombed” structure of the penumbral magnetic field, with some field lines being much more inclined than would be expected from a near-potential situation.

The lower numerical resolution in these penumbra simulations—about 24 km in all directions, as compared to 10–20 km (vertical and horizontal) in the umbrella simulations of Schüssler & Vögler (2006)—probably explains why the magnetic field strengths in the gaps are relatively higher in the penumbra simulations than in the umbrella simulations.

Note that the amplitudes of vertical and horizontal flows are to a large extent determined by energy and mass flux requirements and must be robust properties of the flow; improvements in numerical resolution are expected to primarily cause changes in the magnetic field, which is then forced to locally become more perfectly aligned with the flow. However, lower diffusivity also leads to the development of more small-scale structure and a more chaotic behavior of the magnetic field lines, so it is likely that some level of “turbulent diffusivity” will always be present.

3.2. The Structure and Migration along the Gaps

An important question concerns the inward migration of the gaps. The field lines that are bent down by the ascending and cooling gas cause a reduction of the field strength in the upper parts of field lines that connect to the inward side of the gap, making it easier for gas to come up to the surface on that side. Gaps pushed open by the process described above therefore have a tendency to propagate in the opposite direction of the horizontal flow itself.

This tendency is encouraged additionally by the anisotropy of heat transport near the “head” of the gap, in the following sense: In order to rise into the “opening” the gas must be heated from the umbral-like temperature toward the photospheric one. That heating is mainly due to radiation that “leaks out” sideways, from the edge of the convectively heated gas inside the gap into the less dense and more transparent gas immediately outside.

The magnitude of the horizontal heat flux that is available is a fraction of the nominal vertical solar flux. That amount of flux can support a certain rate of heating per unit volume and time, corresponding to a rather well defined propagation speed that does not too much on other details. But the propagation becomes increasingly difficult with stronger and more vertical fields, so the inward migration of the gap must eventually come to a stop. Beyond that, there is a transition to the umbral dot behavior, defining thus the boundary between the penumbra and the umbra.

4. DISCUSSION

Most present theoretical models of penumbral fine structure are based on the concept of embedded flux tubes. For nearly a decade, the moving tube models (Schlichenmaier et al. 1998a, 1998b; Schlichenmaier 2002) and schematic embedded flux tube models (Solanki & Montavon 1993) have been seen to mutually support each other. We have argued that this congruence is due to a combination of oversimplified models and nonunique interpretations of polarized spectra and images (Spruit & Scharmer 2006; Scharmer & Spruit 2006).

The limitations of these models are indeed fundamental: Attempts to construct models of magnetostatic flux tubes with given (round) cross sections, embedded in a surrounding more vertical field, have been made by Borrero (2007). This leads to an overconstrained problem where magnetostatic equilibrium determines not only the gas pressure, but also the density and thus the temperature within the flux tube. There is no room for an energy equation in these models—the temperature distribution is already determined by the assumed (round) cross section of the flux tube. This highlights the difficulties of satisfying requirements of near-magnetostatic equilibrium with siphon flow and moving tube models; they also generally fail to transport enough heat to the surface.

Even ignoring these difficulties, the agreement between observed and calculated net circular polarization that can be obtained with such models (Borrero et al. 2007a) does not specifically support the existence of penumbral flux tubes, since the magnetic field of its observable part is similar to that of the gap models of Scharmer & Spruit (2006). Also, the evidence recently found for field lines wrapping around bright filamentary structures with strong flows and weaker and more horizontal magnetic field are consistent with both flux tube and gappy models (Borrero et al. 2007b).

Recently, apparent motions of intensity structure across penumbral filaments were observed for several sunspots away from disk center (Ichimoto et al. 2007). These apparent motions were observed only in parts of the penumbra that are perpendicular to the symmetry line and the motions were found to be always in the direction from the limb toward disk center. These observations are difficult to reconcile with (twisting) flux tubes but are consistent with overturning convective flows in gaps (Spruit & Scharmer 2006), with the limb side of the gap hidden by a strongly warped $\tau = 1$ surface (Scharmer & Spruit 2006). Such convective flow patterns are indeed seen in the simulations discussed here.
5. CONCLUSIONS

In this Letter we present a scenario where the Evershed flow is not only related to, but actually is identical to the horizontal component of overturning convection in penumbrae. The observed migration of filament heads toward the umbra is reproduced by the numerical model, and is found to be the result of a pattern motion, with an upflow on the inward side enabled by the bending down of field lines by gas that is cooled at the surface and therefore becomes heavy. This process is aided by lateral radiative heating.

One of the main strengths of this model is that the energy transport and energy balance is at center stage, rather than being an embarrassment as in some other models. In the present scenario energy transport is the controlling factor, relegating issues such as magnetic diffusion to only secondary roles. It is the strong cooling of gas at the surface (seen observationally as the relatively large luminosity of the penumbra) that provides the mechanical driving of the flows, via the resulting pressure differences and pressure gradients. The flows in turn force the magnetic field lines apart and open up the channels that are seen as dark-cored filament in high-resolution observations. In that context the exaggerated magnetic diffusivity in the numerical models mainly has the effect to allow the field lines to slip back through the plasma somewhat too easily; this does not change the overall picture, which is made robust precisely by the strong constraints from the energy transport requirements.

In addition to providing a satisfactory explanation of penumbral fine structure, the present interpretation also allows a unified view of convection and magnetic field interaction in penumbrae (Spruit & Scharmer 2006; Heinemann et al. 2007), umbrae (Schüssler & Vögler 2006), and light bridges (Heinemann 2006). Whereas better observations and simulations may be needed to firmly establish this view, the present 3D MHD simulation already provides a fundamentally more consistent representation of penumbral dynamics and filament formation than 1D flux tube and two-component models.

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