Explanation of the sea-serpent magnetic structure
of sunspot penumbrae

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ABSTRACT

Recent spectro-polarimetric observations of a sunspot showed the formation of bipolar magnetic patches in the mid penumbra and their propagation toward the outer penumbral boundary. The observations were interpreted as being caused by sea-serpent magnetic fields near the solar surface (Sainz Dalda & Bellot Rubio 2008). In this Letter, we develop a 3D radiative MHD numerical model to explain the sea-serpent structure and the wave-like behavior of the penumbral magnetic field lines. The simulations reproduce the observed behavior, suggesting that the sea-serpent phenomenon is a consequence of magnetoconvection in a strongly inclined magnetic field. It involves several physical processes: filamentary structurization, high-speed overturning convective motions in strong, almost horizontal magnetic fields with partially frozen field lines, and traveling convective waves. The results demonstrate a correlation of the bipolar magnetic patches with high-speed Evershed downflows in the penumbra. This is the first time that a 3D numerical model of the penumbra results in downward directed magnetic fields, an essential ingredient of sunspot penumbrae that has eluded explanation until now.

Subject headings: sunspots — Sun: magnetic fields

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1.   Introduction

It is well-known that the sunspot penumbra (the outer part of sunspots) has a very complicate filamentary structure and a strong non-stationary outflow. This outflow is responsible for the so-called Evershed effect, a Doppler shift of the spectral lines emerging from sunspots (Evershed 1909). The magnetic structure of the penumbra can be represented as a mixture of two magnetic field components with different inclinations and strengths (e.g., Degenhardt & Wiehr 1991; Schmidt et al. 1992; Title et al. 1993; Lites et al. 1993; Stanchfield et al. 1997; Bellot Rubio et al. 2004; Sánchez Almeida 2005; Borrero et al. 2005; Beck 2008). However, the radial Evershed flow (in particular, the high-speed 'Evershed coluds') is associated with the more strongly inclined, almost horizontal field (e.g. Title et al. 1993; Shine et al. 1994; Bellot Rubio et al. 2003).

Recently, significant progress in our understanding of the Evershed effect was made by numerical simulations (Heinemann et al. 2007; Scharmer et al. 2008; Rempel et al. 2009a,b; Kitiashvili et al. 2009a). These studies suggested that the Evershed flow is a consequence of overturning magnetoconvection in the presence of inclined magnetic fields, and that the driving mechanism is associated with traveling convective waves that propagate in the direction of the magnetic field inclination (Hurlburt et al. 2000; Kitiashvili et al. 2009a). The issue is not resolved and other interpretations are possible (see Schlichenmaier 2009). Thus, it is important to confront the simulations with as many observations as possible.

In this Letter, we examine the idea that the sea-serpent penumbral field lines detected by Sainz Dalda & Bellot Rubio (2008) in high-resolution Hinode measurements are related to the same mechanism of overturning convection and traveling convective waves in a strong inclined magnetic field. Our analysis is based on the radiative MHD simulations of Kitiashvili et al. (2009a).

2.   Moving bipolar magnetic patches in the penumbra and the sea-serpent model

Analyses of visible and near-infrared spectro-polarimetric observations from the ground revealed that in the mid and outer penumbra the Evershed flows are directed downward and have magnetic polarities opposite to that of the spot (Westendorp Plaza et al. 1997, see Bellot Rubio 2009 for a detailed description). The spectro-polarimeter aboard Hinode (Kosugi et al. 2007; Tsuneta et al. 2008) made it possible to identify isolated magnetic patches of opposite polarity associated with strong, even supersonic, Evershed downflows (Ichimoto et al. 2007; Bellot Rubio 2009; Sánchez Almeida & Ichimoto 2009). This provided

a beautiful confirmation of the results obtained from ground-based observations at lower resolution. Sainz Dalda & Bellot Rubio (2008) then discovered that the opposite polarity patches move radially outward, often accompanied by another patch having the polarity of the spot and being located further away from the umbra. Sainz Dalda & Martínez Pillet (2005) and Ravindra (2006) also detected the evolution of reversed-polarity patches in the penumbra using SOHO/MDI observations (Scherrer et al. 1995), but their bipolar nature could not be established. Taken together, these results provide an indication that the moving magnetic features observed in the penumbra and the Evershed flow belong to the same physical mechanism.

The magnetic patches move between the more vertical filaments of the penumbra with a typical velocity of $0.3 - 1$ km/s, their length is 2–3 arcsec, the mean width is ~ 1.5 arcsec, and they have a lifetime of $0.5 - 7$ hours (Sainz Dalda & Bellot Rubio 2008). Sometimes, the bipolar pairs appear one behind another along the same filament. This can be the signature of a wave-like behavior, similar to the wave behavior of magnetoconvection in the penumbra found in numerical simulations (Kitiashvili et al. 2009a,b).

Based on the observational data, Sainz Dalda & Bellot Rubio (2008) proposed a sea-serpent model which explains the existence of moving bipolar structures as wavering magnetic field lines. In this model, almost horizontal field lines return to the solar interior and then come back to the photosphere, thus forming bipolar patches. This scenario is similar to that discussed by Schlichenmaier (2002) in the context of the moving tube model. It is also similar to the model proposed by Harvey & Harvey (1973) for moving magnetic features in the sunspot moat (MMFs; Sheeley 1969). Indeed, it has been suggested that MMFs represent the continuation of similar features in the penumbra (Sainz Dalda & Martínez Pillet 2005; Ravindra 2006; Sainz Dalda & Bellot Rubio 2008; Kubo et al. 2008).

3. Simulations of magnetic structure and dynamics of sunspot penumbra

For numerical simulations of sunspot penumbra conditions we use the 3D radiative MHD code "SolarBox" (Jacoutot et al. 2008a; Jacoutot et al. 2008b). This code takes into account all essential physics and includes sub-grid scale turbulence modeling based on the large-eddy simulation (LES) approach. A dynamic Smagorinsky turbulence model provides the best agreement with observations in terms of the acoustic oscillation power. However, in these simulations we use a computationally more efficient hyperviscosity model, because it shows results qualitatively very similar to the dynamic model. The code uses a real-gas equation of state, takes into account ionization and excitation of all abundant species in the LTE approximation, and includes radiative transfer and magnetic effects (Ripoli & Wray

2003; Jacoutot et al. 2008a; Kitiashvili et al. 2009a,c).

We simulate the behavior of solar magnetoconvection for an initial background magnetic field of various strengths, from 600 to 2000 G, but with the same inclination of 85° to the vertical axis. Our previous results have shown that these condition provide a very good model for the Evershed effect (Kitiashvili et al. 2009a). The computational domain is $6.4 \times 6.4 \times 6$ Mm^3 and the grid resolution is 50 km. The results were verified using a higher resolution of 25 km and a larger horizontal size of 25 Mm. The lateral boundary conditions are periodic, and we keep the mean initial inclination of the field in the whole box domain by setting up top and bottom boundary conditions that conserve the total magnetic flux, but locally the field strength and inclination can freely change.

The magnetic field strongly influences convective motions. For instance, in the case of vertical magnetic fields, convective granules become smaller with increasing field strength (Stein & Nordlund 2001) and also move faster, generating more high-frequency turbulence (Jacoutot et al. 2008b). A strong inclined magnetic field deforms the granules, making them elongated along the field lines. When the field becomes almost horizontal the convective cells form a filamentary structure, and high-speed flows (reaching 5-6 km/s) appear in the direction of the magnetic field inclination (Kitiashvili et al. 2009a). These flows share many similarities with the observed Evershed flows, including their nearly-supersonic speeds.

For illustration of our results we use a simulation run with initial magnetic field of $B_0 = 1200$ G and inclination angle of 85° pointing in the direction of the horizontal x-axis. Figure 1 shows a time sequence of 2D snapshots of the horizontal and vertical components of the magnetic field, B_x, B_z, and velocity, v_x, v_z, with 8-min cadence for five time moments: 0, 8, 16, 24 and 32 mins. The overplotted curves are projections of the magnetic field lines. The black and white areas seen in the vertical magnetic field (Fig. 1a) correspond to patches of negative and positive polarities. The horizontal magnetic field component (Fig. 1b) shows variations of the magnetic filamentary structure, which is a result of magnetoconvection in the inclined field. The dark areas correspond to "magnetic gaps", areas with a weaker (but not zero) magnetic field, that correspond to observations (Severnyi 1965; Ichimoto et al. 2007). It is clear that the areas of weaker horizontal magnetic field correspond to the transitions between negative and positive polarities of the vertical field. In these transition regions, strong downward flows are observed (Fig. 1c). The transition regions are also characterized by strong $\sim 4 - 6$ km/s horizontal velocities (Fig. 1d). The strongest horizontal flow in the direction of the magnetic field inclination is associated with the negative polarities. The correlation between downflows and negative polarity patches is in agreement with the observations, which show that the downward penumbral motions occur along magnetic fields returning back to the solar surface (Westendorp Plaza et al. 1997; Ichimoto et al. 2007;

Bellot Rubio 2009; Sánchez Almeida & Ichimoto 2009).

Figure 2 displays the 3D structure of magnetic field lines (red curves), temperature variations, and the velocity field (arrows). The top horizontal slice corresponds to the solar surface. The results demonstrate a strong coupling between the fluid flow and magnetic field. In particular, the upflows correspond to magnetic field lines rising above the surface (positive polarity) while the downward flows correlate with the negative polarity. This corresponds very well to the observed properties of the penumbra and the sea-serpent model.

4. Discussion and Conclusion

In this Letter, we have used the results of numerical simulations of magnetoconvection in strong inclined magnetic field to interpret polarimetric observations of a sunspot penumbra. The results reproduce the moving bipolar magnetic elements observed in high-resolution SOHO/MDI and Hinode/SOT data and also their properties, supporting the sea-serpent model proposed by Sainz Dalda & Bellot Rubio (2008). The simulations explain the sea-serpent structure and dynamics of the penumbral field as a consequence of solar magneto-convection in a highly inclined, strong magnetic field, which forms filamentary structures and has properties of traveling convective wave.

The physical picture schematically illustrated in Figure 3 is the following. Convective cells in sunspot penumbrae are deformed under the action of the inclined magnetic field, forming filamentary structures and producing high-speed Evershed flows (Kitiashvili et al. 2009a). The magnetic field lines are stretched by the downward flows and dragged under the surface. The points where the magnetic field lines cross the solar surface are observed as magnetic patches of positive and negative polarities. Note that the negative patch is closer to the umbra, in agreement with the observations. The convective cells move in the direction of the magnetic field inclination because of the traveling convective wave behavior. Therefore, the bipolar magnetic patches also move in the same direction.

Thus, the numerical simulations connect the sea-serpent structure of the moving bipolar magnetic pathes observed in the penumbra with the process of overturning magnetoconvection, traveling convective waves, and the Evershed flow.

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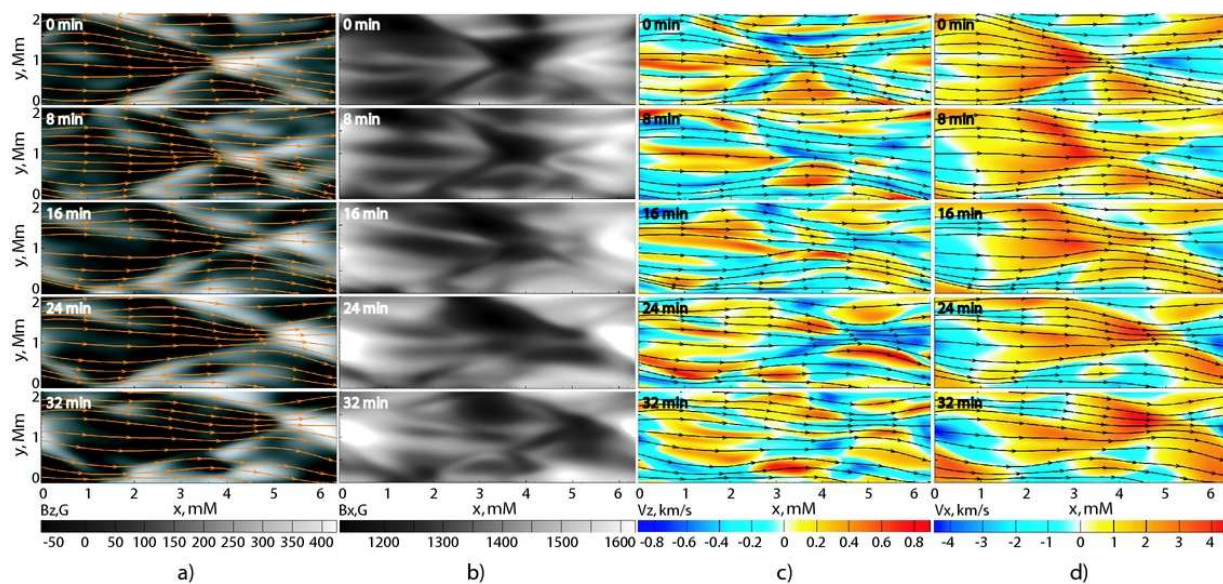
Fig. 1.— Snapshots of the vertical (a) and horizontal (b) components of magnetic field, and the vertical (c) and horizontal (d) components of velocity at the photospheric level for different moments with a cadence of 8 min for the simulations for the initial $B_0 = 1200$G background magnetic field with the 85° inclination angle from the vertical in the x-direction. The overlayed curves are projections of magnetic field lines.
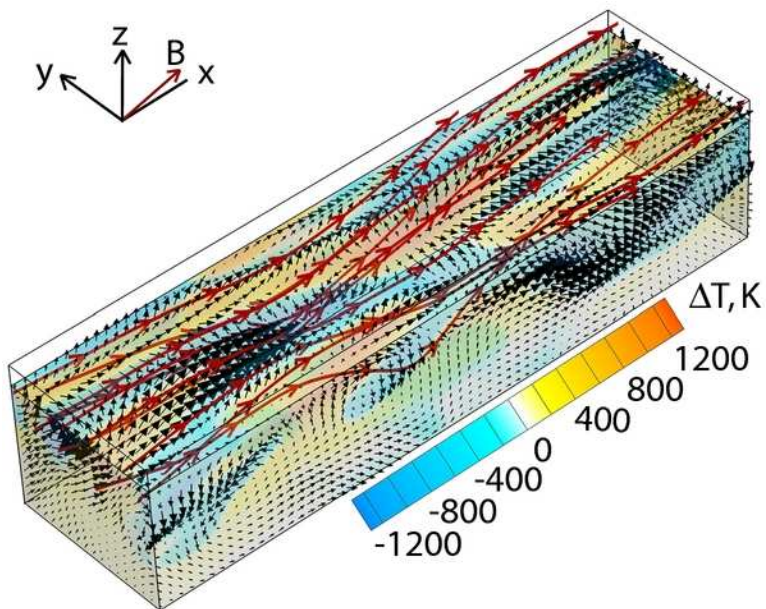
Fig. 2.— 3D rendering of temperature variations, magnetic field lines (red curves) and flow field (arrows).
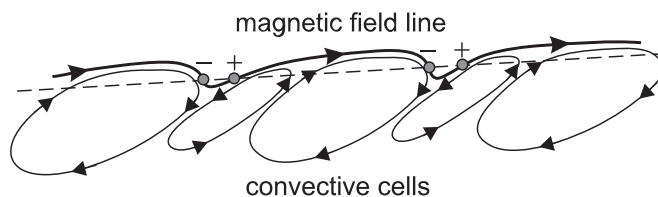

Fig. 3.— Schematic illustration of the sea-serpent model of sunspot penumbra and the moving bipolar magnetic patches. The inclined elliptical curves illustrate streamlines of magnetoconvection in highly inclined magnetic field. The thick solid curve illustrates the sea-serpent behavior of magnetic field lines. Dashed line indicates the solar surface, where the magnetic field is observed.