TRAVELING WAVES OF MAGNETOCONVECTION AND THE ORIGIN OF THE EVERSHED EFFECT IN SUNSPOTS

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ABSTRACT

Discovered in 1909, the Evershed effect represents strong mass outflows in sunspot penumbra, where the magnetic field of sunspots is filamentary and almost horizontal. These flows play an important role in sunspots and have been studied in detail using large ground-based and space telescopes, but the basic understanding of its mechanism is still missing. We present results of realistic numerical simulations of the Sun's subsurface dynamics, and argue that the key mechanism of this effect is in nonlinear magnetoconvection that has properties of traveling waves in the presence of a strong, highly inclined magnetic field. The simulations reproduce many observed features of the Evershed effect, including the high-speed "Evershed clouds," the filamentary structure of the flows, and the nonstationary quasiperiodic behavior. The results provide a synergy of previous theoretical models and lead to an interesting prediction of a large-scale organization of the outflows.

Key words: Sun: magnetic fields – sunspots

1. INTRODUCTION

In the spring of 1909 Evershed published a remarkable discovery of strong horizontal mass flows in sunspots penumbra, the outer part of sunspots characterized by filamentary magnetic field structures (Evershed 1909). The flows, with a typical speed of 1-4 km s⁻¹, start at the boundary between the umbra and penumbra and expand radially, accelerating with distance and suddenly stopping at the outer sunspot boundary. The Evershed effect may play a significant role in the formation, stability, and dynamics of sunspots and is considered one of the fundamental processes in solar physics. This phenomenon caused significant interest and detailed observational and theoretical investigations, but the understanding of the physical mechanism is still missing (a recent review is published by Tritschler 2009).

High-resolution observations from large ground-based telescopes and the *Hinode* space mission revealed a complicated filamentary structure of these flows (Rimmele 1994, 1995; Ichimoto et al. 2007a, 2007b) and their nonstationary dynamics in the form of quasiperiodic "Evershed clouds" (Shine et al. 1994; Rimmele 1994; Georgakilas & Christopoulou 2003; Cabrera Solana et al. 2007, 2008). In some cases, the flows showed a large-scale coherent behavior across several flow channels (Shine et al. 1994), and also provided evidence of a wavelike behavior (Rimmele 1994; Georgakilas & Christopoulou 2003).

Theories of the Evershed effect can be divided in two categories, describing it as channel flows in magnetic flux tubes (Meyer & Schmidt 1968; Montesinos & Thomas 1997; Schlichenmaier et al. 1998) or as elongated magnetoconvective rolls (Danielson 1961; Busse 1987; Hurlburt et al. 2000). Recent numerical simulations (Heinemann et al. 2007; Rempel et al. 2009) successfully modeled the filamentary magnetic structure of sunspot penumbra and horizontal outflows, thus providing a strong support to the magnetoconvective nature of the Evershed effect (Scharmer et al. 2008).

In this paper, we present a study of solar magnetoconvection in the presence of an inclined magnetic field, based on the realistic radiative MHD simulations, and link the Evershed effect to the phenomenon of traveling magnetoconvection waves. The convective waves are a very interesting MHD phenomenon (Weiss 1991), which, in fact, has been previously suggested as a reason of the Evershed flows (Hurlburt et al. 2000), but did not receive further development. Our study provides a basis for explaining the Evershed effect as a result of traveling magnetoconvection waves in a highly inclined magnetic field of sunspot penumbra. The phenomenon of traveling magnetoconvection waves is considered also in the dynamics of the Earth's core (Walker & Barenghi 1999; Zhang 1999), and may happen in various astrophysical objects, such as magnetic stars, accretion disks, compact objects, and active galactic nuclei. Thus, detailed observational and theoretical studies of this phenomenon are of great interest.

2. NUMERICAL SIMULATIONS

We use a three-dimensional (3D) nonlinear radiativemagnetohydrodynamics code developed for simulating the upper solar convection zone and lower atmosphere (Jacoutot et al. 2008a, 2008b). This code takes into account several physical phenomena: compressible fluid flow in a highly stratified medium, 3D multigroup radiative energy transfer between the fluid elements, a real-gas equation of state, ionization and excitation of all abundant species, and magnetic effects. An important feature of this code is implementation of various subgrid scale turbulence models. In this paper, we adopted the most widely used Smagorinsky model (Smagorinsky 1963) in the compressible formulation (Moin et al. 1991; Germano et al. 1991). The turbulent electrical conductivity is calculated by using the extension of the Smagorinsky model to the MHD case (Theobald et al. 1994).

We simulate the upper layer of the convection zone, extending from 5 Mm below the visible surface to 0.5 Mm above the surface. The horizontal size varied from 6.4 Mm \times 6.4 Mm to 25 Mm \times 25 Mm. The computational grid step size varied from 25 to 100 km. The results of this paper are obtained using a 128³ grid with a step size of 50 km (except Figure 5, which is obtained



Figure 1. Snapshot of the 3D simulations of subsurface solar convection in a region of an inclined magnetic field. The initial field strength, B_0 , is 1000 G, the inclination angle, α , is 85° with respect to the vertical. Red curves show magnetic field lines; the color 3D structures show the temperature variations relative to the mean vertical stratification (dark green and blue correspond to lower temperature); the arrows show the velocity field. The horizontal size of the box is 6.4 Mm, and the depth is about 2.5 Mm.

using a 64³ grid). We have verified that the results do not change in computations with finer grids (except the development of smaller scale turbulent motions).

The initial uniform magnetic field is imposed on a snapshot of the pre-existing hydrodynamic convection (Jacoutot et al. 2008b). The initial field strength, B_0 , varies from 0 to 2000 Gauss, and the inclination angle, α , varies from 0° to 90°. The lateral boundary conditions are periodic, and the top and bottom boundary conditions maintain the total magnetic flux and the mean inclination. This formulation allows us to carry out a series of controlled numerical experiments and investigate how the structure and dynamics of solar turbulent convection depend on the magnetic field properties in regimes close to the observed in sunspot penumbra, and elucidate the physical mechanism of the Evershed effect.

3. RESULTS

Outside magnetic field regions the solar convection forms granular cells of a typical size of 1-2 Mm and lifetime of about 10 minutes. In the presence of magnetic field the structure of convection strongly depend on the field strength and inclination. When the magnetic field is vertical the granules become smaller (Stein & Nordlund 2002), and their overturn time is shorter resulting in generation of high-frequency turbulence and acoustic waves ("halos;" Jacoutot et al. 2008b). In the presence of an inclined magnetic field, such as that observed in sunspot penumbra, the granular cells become naturally elongated in the direction of the field because magnetic field restricts motions across the magnetic field lines. But the most interesting effect is that the inclined field changes the nature of solar convection. Instead of a stationary overturning convection pattern the simulation reveals traveling convection waves, which become more apparent and stronger for higher field strengths and inclination. This convection develops long narrow structures of velocity, thermodynamic parameters and magnetic field, resembling the



Figure 2. Gray-scale maps show snapshots of the magnetic field component, B_x , in the direction of the field inclination, and arrows show the horizontal velocity at the solar surface for different initial magnetic field strength, B_0 : (a) 1000 G, (b) 1200 G, and the inclination angle, $\alpha = 85^{\circ}$.

filamentary structure and motions in the penumbra of sunspots. These structures are illustrated in Figures 1 and 2.

Figure 1 shows a 3D slice of our computational domain with a sample of magnetic field lines (red curves), velocity field (black arrows), and a volume rendering of the temperature structures (blue-red color scale). The initial 1000 Gauss magnetic field is oriented in the xz-plane and inclined by 85° to the z-axis, so that the *B*-vector is positive in the *x*-direction. Evidently the strongest motions occur in the direction of the field inclination (corresponding to the outward direction in sunspots) in narrow structures, with upflows and downflows at the initial and end point of these structures. The magnetic field lines change in accord with these elongated motions, rising up at the initial points and declining at the end points, thus giving an impression of rising and falling loop-like motions. The temperature is typically higher at the start points and lower at the end points. The typical vertical velocity around these points is about 1 km s^{-1} , but the horizontal velocity between them in the positive x-direction reaches $4-6 \text{ km s}^{-1}$. Most of the horizontal mass flows occur in these relatively narrow patches, which strongly resemble "Evershed clouds," discovered in observations (Shine et al. 1994). Significantly weaker flows in the opposite direction are also observed. These often originate at the initial upflow points. Vertical cuts through the flow field (e.g., left yz-plane



Figure 3. Same as Figure 2 but a vertical *xz*-plane cut for $B_0 = 1000$ G and $\alpha = 85^{\circ}$.

in Figure 1) reveal associated vortex-type motions below the surface.

When the background field is strong, the horizontal flow patches become quite narrow, with a width of 0.5 Mm or less. The magnetic field variations also becomes more filamentary. This is illustrated in Figure 2, which shows the surface structure of the horizontal flows and the B_x component for two different initial magnetic field strengths, 1000 and 1200 G. The simulations show strong interaction between the plasma flows and magnetic field. The magnetic field controls the general direction of the flows, but in the strong flow patches, the magnetic field strength. This may give impression, sometimes, reported from observations that the flows occur in magnetic field "gaps." Nevertheless, the plasma flows are strongly coupled.

The most interesting feature of the simulations, which, we argue, is a key for understanding the Evershed effect, is the traveling wave pattern of magnetoconvection in the presence of a strongly inclined magnetic field. The simulations show that the velocity patches and magnetic field perturbations migrate in the direction of the field inclination. Vertical cuts in *xz*-planes show rapidly moving inclined convective cells (a snapshot is illustrated in Figure 3). This process is best seen in the movies,⁴ and also in the time-distance slices of the surface V_x velocity component along the *x*-axis. Figure 4 shows an example of these slices for the initial magnetic field, $B_0 = 1200$ G, and the inclination angle of 85°. In this case the convective velocity reaches ~6 km s⁻¹, and a pattern of convection waves traveling in the direction of the field inclination with a speed of 1-2 km s⁻¹ can be identified.

The general picture is that the overturning convection motions are swept by the traveling waves. This interaction amplifies the flows in the direction of the waves. This is accompanied by weaker plasma motions in the opposite direction. In fact, the initial points of the convective upflows often move in the opposite direction. This may explain the puzzling discrepancy between the outward flow direction and the apparent motion of "penumbra grains."

It is intriguing that the traveling convection pattern shows variations with a characteristic time of 20–50 minutes, resembling the quasiperiodic behavior noticed in the observations (Shine et al. 1994; Rimmele 1994; Georgakilas & Christopoulou 2003). By increasing the computational domain up to 25 Mm we have checked that the quasiperiodicity does not depend on the size of the domain and, thus, is not due to the periodic boundary condition. This is an intrinsic property of the inclined field magnetoconvection, but understanding of this phenomenon requires further investigation.



Figure 4. Time-space slice of the velocity component, V_x , in the direction of the field inclination for $B_0 = 1200 \text{ G}$, $\alpha = 85^\circ$. For reference, the white dashed line shows a speed of 4 km s⁻¹.

As we have pointed out the high-speed $(4-6 \text{ km s}^{-1})$ horizontal flows occur in localized patches corresponding to the "Evershed clouds." An average over time and space velocity is smaller, about $1-2 \text{ km s}^{-1}$. The flows are concentrated in a shallow subsurface layer less than 1 Mm deep (Figure 5(a)). The velocity peaks about 100–200 km below the surface. This also corresponds to the observations showing that the velocity of the Evershed flows increases with depth. The averaged velocity does not change much with the magnetic field strength in the range of 1000–1500 G, but it strongly depends on the inclination angle (Figure 5(b)). The mean horizontal flow is much weaker for small inclination angles.

4. DISCUSSION

The radiative MHD simulations of solar magnetoconvection in regions of inclined magnetic field qualitatively and quantitatively describe many observed features of the Evershed effect in sunspots. The results indicate that the principal physical mechanism of the Evershed flows is the traveling wave nature of magnetoconvection. The traveling waves have been extensively studied in idealized situations (Weiss 1991; Hurlburt et al. 1996), and it has been suggested that they play a significant role in sunspot flows (Hurlburt et al. 2000). Our simulations model this phenomenon in the realistic solar conditions, and show that indeed many details correspond to the observations, thus providing a basis for explaining the Evershed effect.

In particular, the simulations show that the high-speed flows reaching $4-6 \text{ km s}^{-1}$ occur in the direction of the field inclination in narrow, 2-3 Mm long patches, which tend to appear quasiperiodically on a timescale of 15–40 minutes. These patches correspond to the so-called "Evershed clouds" (Shine et al. 1994; Rimmele 1994; Cabrera Solana et al. 2007) and represent the main component of the Evershed flows. These horizontal flows originate from convective upflows of hotter plasma, as in ordi-

⁴ http://soi.stanford.edu/~irina/ApJL/movies.html



Figure 5. Distributions of the subsurface horizontal velocity component, V_x , with depth, z: (a) for the magnetic field strength of 600, 1000, 1200, and 1500 G, and the inclination angle, $\alpha = 85^{\circ}$; (b) $B_0 = 1200$ G, $\alpha = 0^{\circ}$, 15° , 30° , and 85° .

nary convection, but are channeled by the magnetic field and amplified by the traveling convective waves. The whole process is highly nonlinear and stochastic with high-speed patches appearing randomly, but the simulations also show large-scale organization patterns across the simulation domain, which seem to be associated with the traveling waves. These patterns are evident in the simulation movies. Some observations showed a signature of coherence in appearance of the Evershed clouds (Shine et al. 1994) but this has not been fully established (Georgakilas & Christopoulou 2003). The simulations suggest that a large-scale coherence may be a fundamental property of the traveling wave phenomenon, and certainly encourage further observational studies. Of course, in real sunspots the magnetic field stricture is highly inhomogeneous, and this may affect the large-scale appearance. This must be investigated in future simulations.

In the past several models were suggested to explain the Evershed effect. Interestingly, some features of these models can be found in our simulations. One of the first models describes the penumbra filaments as convective rolls along the direction of magnetic field (Danielson 1961; Busse 1987), suggesting the convective nature of the Evershed effect. The apparent observed wave-like behavior inspired attempts to explain the Evershed effect as magnetoacoustic or magnetogravity waves (Maltby & Eriksen 1967; Bunte et al. 1993). Our model specifies that these waves are convective in nature. The rising and falling thinflux tube model (Schlichenmaier et al. 1998) was suggested to describe the discrepancy between the apparent motion of penumbra features and the main Evershed flows. Our simulations explain this naturally, and also reveal upward and downward loop-like motions of magnetic field lines synchronized with the high-velocity patches. The siphon model (Meyer & Schmidt 1968; Montesinos & Thomas 1997) suggested that the flow is driven by the pressure difference between the initial and end points, and indeed, in the simulations the gas pressure in the initial points is higher than at the end points. The recent numerical simulations of the sunspot structure (Heinemann et al. 2007; Rempel et al. 2009) led to the suggestion that the Evershed effect is caused by the overturning convection (Scharmer et al. 2008), but the flow speed was not sufficiently high. Our simulation show that the high-speed matching of the observations is achieved if the magnetic field is strong, 1000-1500 G, and highly inclined, when the magnetoconvection has properties of

traveling waves. Thus, it seems that the MHD simulations provide a unified description of the models and the key observed features, and, perhaps, lead to the understanding of the 100-year old discovery.

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