Subsurface structure of the Evershed flows in sunspots

2011 J. Phys.: Conf. Ser. 271 012076

(http://iopscience.iop.org/1742-6596/271/1/012076)

Journal of Physics: Conference Series **271** (2011) 012076 doi:10.1088/1742-6596/271/1/012076

Subsurface structure of the Evershed flows in sunspots

Irina N. Kitiashvili[1], **Alexander G. Kosovichev**[1], **Nagi N. Mansour**[2], **Alan A. Wray**[2]

[1]Stanford University, Stanford, CA 94305, USA

[2]NASA Ames Research Center, Moffett Field, CA 94040, USA

E-mail: `irinasun@stanford.edu`

Abstract. The radial outflows in sunspot penumbrae, known as the Evershed effect, are of significant interest for understanding the dynamics of sunspots. Local helioseismology has not been able to determine the depth of these flows nor their relationship to mass circulation in sunspots. Recent radiative MHD simulations have provided a convincing explanation of the Evershed flow as a natural consequence of magnetoconvection in the strongly inclined magnetic field region of the penumbra. The simulations reproduce many observational features of penumbra dynamics, including the filamentary structure, the high-speed non-stationary "Evershed clouds", and the "sea-serpent" behavior of magnetic field lines. We present the subsurface structure of the Evershed effect, obtained from numerical simulations, and determine the depth of the radial outflows for various magnetic field strengths and inclinations. The simulations predict that Evershed flows are rather shallow and concentrated in the top 0.5 – 1 Mm layer of the convection zone. This prediction can be tested by local helioseismology methods.

1. Introduction

Investigation of the high-speed radial outflows in sunspots ("Evershed flows", [2]) has a century-long history. However, only recently has it become possible to obtain detailed high-resolution observations and to construct close-to-reality numerical models. The improvement of observational capabilities has led to different models of sunspot penumbrae and Evershed flow; however, these models, listed in Table 1, can explain only some observational features. Recent improvements in computational capabilities have led to the development of realistic MHD simulations [3, 10]; these have revealed connections between overturning convection and radial outflows in the inclined magnetic field of sunspot penumbrae.

To explore the idea of overturning convection in a sunspot penumbra, we have performed realistic radiative MHD simulations using the "SolarBox" code [4] and have compared the simulation results with observational features. The code was developed at the NASA Ames Research Center and the Stanford Center for Turbulence Research for numerical simulation of the top layers of the convective zone and lower atmosphere. It solves the radiative MHD equations with real gas effects in a rectangular computational domain. The code is based on a LES (Large-Eddy Simulation) formulation and includes various subgrid-scale turbulence models. It takes into account several physical phenomena: compressible fluid flow in a highly stratified medium, three-dimensional multi-group radiative energy transfer between the fluid elements, a real-gas (tabular) equation of state, ionization and excitation of all abundant species, and magnetic effects.

Table 1. Models of a sunspot penumbra.

Model	Ref.	Model	Ref.
Magnetic field gaps	[11]	Thin magnetic flux tube model	[9]
Siphon model	[7, 12]	Overturning convection	[3, 10]
Convective rolls	[1]		

In the paper, we use the fields from numerical simulations described in [5], and discuss the subsurface structure of magnetoconvection in highly inclined magnetic fields.

2. Realistic simulations of the solar convection in an inclined magnetic field

Construction of a realistic sunspot penumbra model is a complicated problem, in particular because it is a part of a sunspot, where strong plasma inhomogeneities co-exist with magnetic fields of highly variable structure and strength. To simplify the problem, we perform separate numerical simulations of different regions of a penumbra, regions in which the mean magnetic field inclination and strength have different values; these quantities have constant spatial averages in each simulation. In this manner, the results of the simulations for different magnetic field strengths and inclinations can be associated with areas located at different distances from the sunspot umbra. In the simulations that will be discussed, the magnetic field varies from 2000 G to 600 G, and the mean inclination of the field is approximately 85° from the surface normal [5].

Figure 1 shows 3D snapshots of the subsurface structure of magnetoconvection for an initial magnetic field strength of 1200 G at 85° inclination. Distributions of the horizontal magnetic field, the kinetic energy, and the magnitude of vorticity are shown. The superimposed curves show selected magnetic field lines to indicate the topology of the magnetic field.

At the surface, the magnetic field has a filamentary structure represented by elongated areas of strong magnetic field along the direction of the field inclination. In the inclined field, strong horizontal velocities are observed with values up to 2 – 4 km/s and occasionally as high as 6 km/s ("Evershed clouds"). The magnetic filaments are a result of the influence of narrow high-speed

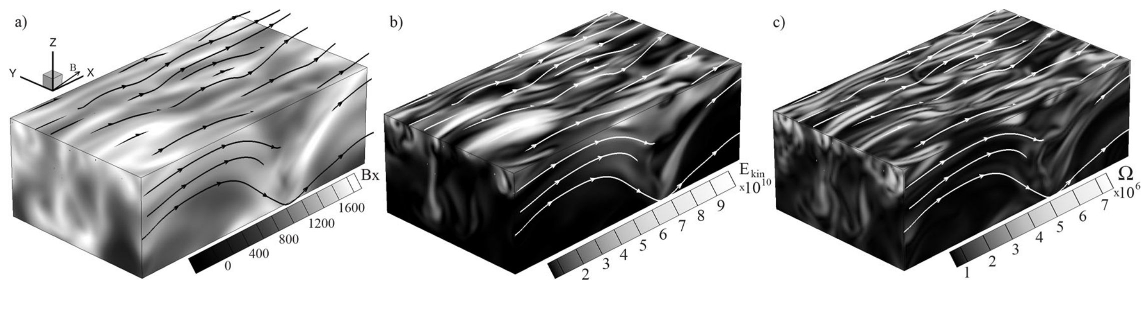

Figure 1. 3D snapshots show distributions of a) the horizontal magnetic field, b) kinetic energy and c) magnitude of vorticity. Curves show the topology of the magnetic field with selected field lines.

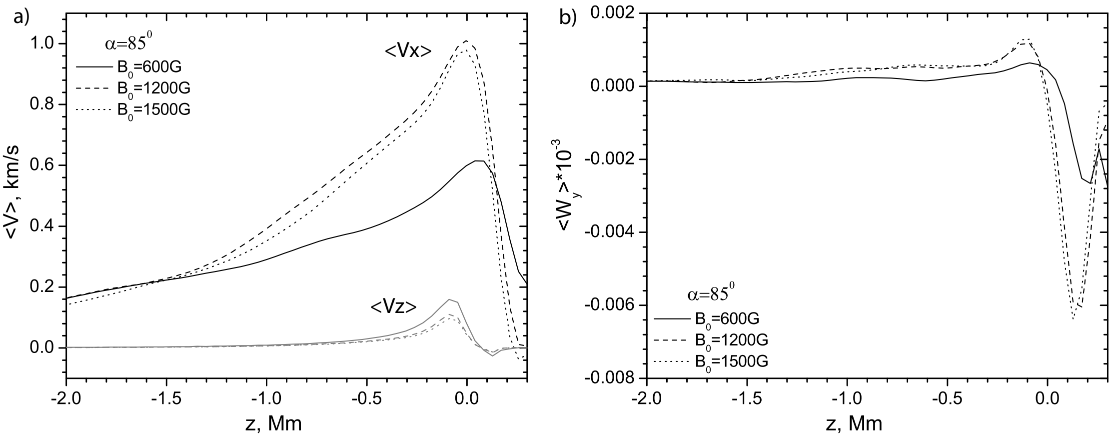

Figure 2. Vertical distribution of the horizontal, <Vx>, and vertical, <Vz>, velocities (panel a) and the y-component of vorticity (panel b) for initial magnetic field strengths of 600, 1200 and 1500G, and inclination $\alpha = 85°$ from vertical.

horizontal flows. These flows push the magnetic field aside and thus cause concentrations of field at the boundaries of the high-speed regions [5]. An additional effect on the field topology is caused by partially frozen magnetic field lines in the plasma. In this situation, upflows of stretched convective cells and downflows between them cause deformation of the magnetic field lines, thus forming thin and wavy magnetic flux tubes (Fig. 1) that are observed as the "sea-serpent" effect [6, 8]. Thus, convective flows in the inclined magnetic field regions of the penumbra form narrow magnetic tubes that demonstrate a complicated oscillatory behavior along the surface in the direction of the field lines and also in the plane perpendicular to the field inclination. The kinetic energy distribution in Figure 1b shows strong local concentrations in the subsurface layers, representing the Evershed flow. The magnitude of vorticity (Fig. 1c) shows concentration of vortical motions along and perpendicular to the field inclination near the surface. The mean horizontal and vertical flows are shown in Figure 2a. The simulations show subsurface vortical motions mostly in the direction perpendicular to the direction of inclination of the mean magnetic field. The magnitude of vorticity increases for stronger magnetic field strengths (Fig. 2b). It is $4 - 5$ times smaller in the subsurface layers than at the surface.

Form a physical point of view, the inclination of the magnetic field plays the principal role in creation of subsurface shear flows, the Evershed effect. This inclination breaks the symmetry of the convection and causes deformation of the convective cells that appear as traveling convective waves. By examining the mean Reynolds and Maxwell stresses (Fig. 3), we find that the Maxwell stress is the main source of the mean shear flow – Evershed effect.

3. Conclusion

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. Realist numerical simulation results indicate that the principal physical mechanism of Evershed flows is related to two effects: 1) the filamentary structurization of convective cells in a strongly inclined magnetic field, and 2) the traveling-wave nature of the magnetoconvection. Our simulations model this phenomenon in realistic solar conditions and reproduce many details of the observations, thus providing a basis for explaining the Evershed effect.

The simulation results provide a synergy of earlier proposed models: propagation of flows in weakly-magnetized gaps in the magnetic field [11], the thin-flux-tube model [9] (Fig. 1), the

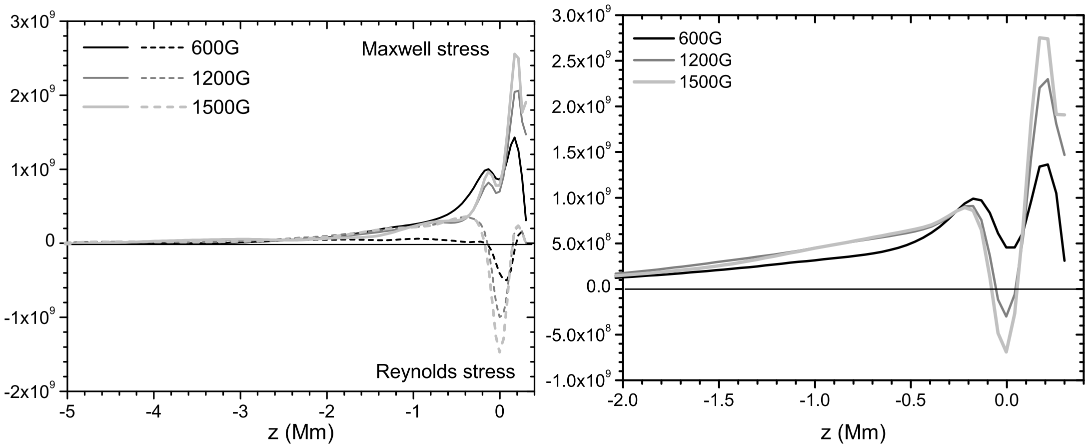

Figure 3. Variations of the Maxwell and Reynolds stresses (left panel), and their sum (right panel) obtained from the simulation results for initial magnetic field strengths of 600, 1200 and 1500 G, inclined at 85° from vertical.

siphon model [7], the overturning convection model [10], and the convective rolls model [1]. In particular, our analysis shows that the oscillatory behavior of the convective rolls in the last model has some similarities with the simulation results. As indicated by this theory, the balance between the Reynolds and Maxwell stresses (Fig. 3) in subsurface layers can be a driving force of the Evershed effect. The horizontal flows originate from convective upflows of hotter plasma, as in ordinary convection, but are channeled by the magnetic field and amplified by the traveling convective waves. The whole process is highly non-linear and stochastic, with high-speed patches appearing randomly, but the simulations also show large-scale organized patterns across the simulation domain. This pattern seem to be associated with traveling waves. The simulations suggest that the Evershed flow is rather shallow, concentrated in the top 0.5 – 1 Mm of the convection zone (Fig. 2a). This prediction may be tested by local helioseismology methods.

References

[1] Busse F H 1987 A new mechanism for the Evershed flow. *Proc. of the Inaugural workshop* 187.
[2] Evershed J 1909 Radial movement in sun-spots. *MNRAS* **69** 454.
[3] Hurlburt N E, Matthews P C and Proctor M R E 1996 Nonlinear compressible convection in oblique magnetic fields. *ApJ* **457** 933.
[4] Jacoutot L, Kosovichev A G, Wray A and Mansour N N 2008 Realistic numerical simulations of solar convection and oscillations in magnetic regions. *ApJ* **684** L51.
[5] Kitiashvili I N, Kosovichev A G, Wray A A and Mansour N N 2009 Traveling waves of magnetoconvection and the origin of the Evershed effect in sunspots. *ApJ* **700** L178.
[6] Kitiashvili I N, Bellot Rubio, L R, Kosovichev A G, Mansour N N Sainz Dalda A and Wray A A 2010 Explanation of the sea-serpent magnetic structure of sunspot penumbrae. *ApJ* **716** L181.
[7] Meyer F and Schmidt H U 1968 The Evershed effect as a wave phenomenon. *Mitteilungen der Astronomischen Gesellschaft Hamburg* **25** 194.
[8] Sainz Dalda A and Bellot Rubio L R 2008 Detection of sea-serpent field lines in sunspot penumbrae. *A&A* **481** L21.
[9] Schlichenmaier R, Jahn K and Schmidt H U 1998 A dynamical model for the penumbral fine structure and the Evershed effect in sunspots. *ApJ* **493** L121.
[10] Scharmer G B, Nordlund Å and Heinemann T 2008 Solar surface magneto-convection. *ApJ* **677** L149.
[11] Severnyi A B 1965 The Nature of solar magnetic fields (The fine structure of the field). *Soviet Astronomy* **9** 171.
[12] Thomas J H 1988 Siphon flows in isolated magnetic flux tubes. *ApJ* **333** 407.