MAGNETOCONVECTION AND MICROPOROS

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ABSTRACT

We report on results from a series of radiative magnetoconvection simulations in a 12 Mm × 12 Mm × 3 Mm near-surface solar layer. Initially unipolar, vertical magnetic field at average field strengths of 0 G, 200 G and 400 G is imposed on a fully relaxed hydrodynamically convective state. Magnetic field is swept to the intergranular boundaries by the convective flows, where it is compressed to kilogauss field strengths. The shapes and intensities of magnetic features typically evolve on the same time scale as the granulation pattern; however, the underlying magnetic structure evolves on a much longer time scale.

Occasionally, dark, high field strength features form that have properties consistent with observed micropores. The micropores primarily form when a small granule submerges and the surrounding magnetic field moves into the resulting dark ‘hole’. The fluid flow inside micropores is suppressed by the strong magnetic field. The surrounding walls of a micropore heat its edges by lateral radiation, but the micropore experiences a net cooling through vertical radiation. The resulting thermodynamic structure of micropores stabilize them against destruction, allowing some micropores to exist for many granulation time scales.

Key words: Convection; Magnetic fields.

1. INTRODUCTION

We have conducted a series of magnetoconvection simulations to investigate the interaction between magnetic field and convection on the scale of granulation. While much progress has been made observationally in the study of small-scale magnetic features (such as bright points), it is difficult to trace the evolution of features that do not have well correlated proxies (such as micropores) (e.g., Berger & Title 2001). We use the simulations to investigate if micropores can form through the merger of existing magnetic flux.

The numerical approach is based on the hydrodynamic code of Nordlund and Stein (Stein & Nordlund 1998; Nordlund & Stein 1990), modified to include magnetic fields. The physical region under investigation is a thin solar surface layer. The dimensions are 12 Mm × 12 Mm × 3 Mm, extending 500 km above the surface to the temperature minimum and extending 2.5 Mm below the surface into the convection zone. The simulations are run on a three-dimensional non-staggered Cartesian grid. We solve the equations for mass, momentum and internal energy conservation and the induction equation for the vector potential. Pressure and temperature are found from a tabular equation of state, which includes ionization. The simulations include non-gray, LTE radiative transfer using a 4-bin opacity distribution function. The boundaries are periodic in the horizontal directions, and open in the vertical direction, with the magnetic field tending toward a potential field at the top boundary.

The initial state for the simulations was created from a snapshot taken from an existing lower resolution, hydrodynamic simulation. The snapshot was then interpolated to the desired resolution and physical size and allowed to relax thermally. The resulting initial state was used to start three simulation runs, each differing by the magnitude of the initial vertical field strength. All imposed fields were unipolar. Each of the scenarios was run for approximately three hours of solar time.

1. Bx,0 = By,0 = Bz,0 = 0 at each grid point. This is a control run representing the purely hydrodynamical state.

2. Bx,0 = By,0 = 0, Bz,0 = 200 G at each grid point. This case represents a moderate field strength plage region.

3. Bx,0 = By,0 = 0, Bz,0 = 400 G at each grid point. This case represents a high field strength plage region.


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2. STRUCTURE OF MICROPORES

Magnetic field is swept to intergranular boundaries by the divergent upflows inside granules. The magnetic is compressed into “flux sheets” in the intergranular lanes and “flux tubes” at the intergranular vertices. At least near the surface, these tubes are not symmetric, isolated structures, but form star-shaped patterns and often are connected to nearby “flux sheets”.

A typical simulation micropore has an area given by its intensity signature ($I < 0.8 < I >$) in the range $1 - 2 \text{ Mm}^2$. The magnetic size is slightly larger, as the edges of magnetic structures are brighter where material flows down along the current sheet. The micropores have fluxes of $1.5 - 3.0 \times 10^{10} \text{ Mx}$. They evolve on the timescale of granulation, with only a few lasting for several granule turnover times. The sizes, intensities and fluxes are consistent with the smallest observed pores (Keil et al. 1999; Leka & Skumanich 1998; Sütterlin 1998). Micropores are strong magnetic field concentrations where the unit optical depth surface is at a lower temperature than the surrounding medium, causing the micropore to appear dark (Figure 1). The temperature structure inside is superadiabatic, causing the micropore to cool and become partially evacuated. Weaker field concentrations show downflow throughout their interiors, but the velocities inside micropores are suppressed due to higher field strengths; downflows still exist through a sheath at the outer boundary, however (Figure 2). The suppression of velocity in the micropore interior leads to a reduction in the convective energy transport. Radiative transport becomes a more important factor in the balance of energy. The micropores are cooled by radiation in the vertical direction and heated by radiation from their hot sidewalls (Figure 3). The vertical cooling is nearly balanced by the horizontal heating and the micropore structure is fairly stable.

3. FORMATION OF MICROPORES

The formation process for a micropore is shown in Figure 4. The left panel shows a mask where high field strength points ($B > 1.5$) and low emergent intensity points ($I < 0.8 < I >$) are dark. A high-field, dark ring forms first, with the interior subsequently decreasing in intensity and rising in field strength. The middle panel shows the emergent intensity for the same times. A small granule near position (1.5, 2.5) is in the process of disappearing, leaving behind a dark hole. The magnetic field is shown in the right panel. The disappearing granule is surrounded by magnetic field that gets pushed into the space the granule leaves behind. There is a gradient in the magnetic field strength at the interface between a granule and intergranular lane, with weaker field closest to the granule and increasing into the lane. Therefore, weaker field enters the dark region first. Once the magnetic field fills the region left behind by the sinking granule, it is compressed to high field strength by surrounding granules. The merger process described here is an alternative method of formation to the emergence of a monolithic flux structure. This type of formation process is similar to that seen in network bright point observations, which has been named formation by granule compression (Muller & Roudier 1992). The network bright points appear to form in large, dark spaces between granules as the magnetic field gets compressed by converging granules. The formation time was found to be rapid, occurring in approximately four minutes. Further observations have confirmed the process in the network (Roudier et al. 1994) and also in plage regions (Berger & Title 2001).

4. CONCLUSIONS

A series of numerical simulations was used to investigate magnetic fields in a convectively unstable atmosphere in order to get a better understanding of the interactions and features seen in solar observations. The general properties of the magnetic field agree well with observations. Magnetic field is transported from granules to intergranular lanes by convective flow. The field gathers in the intergranular lanes and is compressed. Magnetic features form preferentially at the vertices of intergranular lanes.

The simulations have shown a possible formation mechanism for micropores. Existing field emerges at the site of a disappearing granule. The formation process must be relatively fast (less than a granular turnover time). Some micropores are large enough to survive for more than a few convective turnover time scales. Even though these structures survive, they are constantly being deformed and squeezed into the intergranular lanes by changes in the granulation pattern. Over the course of their lifetimes, larger magnetic structures undergo many splittings and mergers. This dynamic evolution can cause the magnetic features to lose their intensity signature while still being a coherent magnetic structure, suggesting that their evolution cannot be traced (at least in its entirety) by these signatures. A longer time span is necessary to make a statistical study of micropores. The scope of the investigation here is limited to plage-like conditions, and it would be useful to study other field topologies. However, even with a limited number of samples, we now have data to get radiation diagnostics, such as Stokes profiles, for three-dimensional magnetic features.

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Figure 1. Background: filled contours of the magnetic field in 250 G intervals. Overlay: contours of the temperature from 4000 K to 16000 K in 1000 K intervals. The $\tau = 1$ depth is shown as the thick line around $z = 0$ Mm. The “flux tubes” are significantly cooler than their surroundings at a given geometrical depth.

Figure 2. Background: filled contours of the magnetic field in 250 G intervals. Overlay: velocity field. The $\tau = 1$ depth is shown as the thick line around $z = 0$ Mm. The flow is suppressed in the interior of the strong established flux tube in the center, but not the evacuating “flux tubes” on either side.
Figure 3. Radiative heating and cooling. Units are $10^{10}$ erg g$^{-1}$ s$^{-1}$. The top three panels show the net radiative heating/cooling and its relation to the temperature and magnetic fields. The bottom three panels show the contribution of vertical, inclined and nearly horizontal rays. The interior of the strong established “flux tube” is nearly in radiative equilibrium, with cooling by vertical rays nearly balanced by horizontal heating from the side walls.
Figure 4. Images of magnetic field (right panels), emergent intensity (center panels) and a mask showing only low intensity, strong field locations (left panels). Micropores form when magnetic flux from surrounding intergranular lanes moves into locations where a small granule disappears.