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The Decay of a Simulated Pore

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Abstract.
Using MURaM – **M**ax-Planck Institut für Aeronomie **U**niversity of Chicago **Ra**diative **M**agnetohydrodynamics – an MHD code which includes radiative transfer and partial ionization, we have studied the decay phase of a solar pore. The simulations are sufficiently realistic in their treatment of the photosphere to allow a direct comparison with observations, both current and those of upcoming missions such as Solar-B. As well as discussing the structure and decay of pores, we show the formation of shallow, field aligned, convective rolls which are an important feature of our solutions.

1. Introduction

In the coming years we can expect to see new observations providing constraints for some long standing mysteries, whilst also revealing some new puzzles. One area where such new constraints and puzzles can be expected concerns pores and sunspots, as demonstrated by Scharmer et al. (2002) who recently found "hairs" and "canals" in the vicinity of pores. Complementary to these new observations are new simulations which include the physics to allow us to directly compare the observations with theory. The known, fully three-dimensional, structure of the simulations then allows us to interpret and understand the observations.

The MURaM code (Vögler 2003; Vögler et al. 2003) solves the MHD equations taking into account both radiation (in either the gray approximation or using opacity binning) and partial ionization. It produces "realistic" simulations of magnetoconvective phenomena in the convection zone up to the top of the photosphere. We have performed simulations, using the MURaM code in order to investigate what happens when we begin with a pore and let the system evolve. Diagnostic tools can then be used to determine the appearance of the atmosphere in various spectral lines and groups of lines. In this paper we present some results from this calculation.

2. The Simulation

We have used a computational box which is 12000 km long in each of the horizontal directions and 1400 km high. The visible ($\tau = 1$) surface is approximately

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400 km from the top of the box. We have used 288 grid points in both horizontal directions and 100 grid points in the vertical direction.

All the (vertical) sidewalls are treated as periodic. This is acceptable as the simulated pore occupies only a small fraction of the domain and thus feels little influence from the periodicity. The upper and lower boundary conditions are more complicated because the pore enters the box from below and emerges through the top boundary. The current study employs a closed upper and open lower boundary. Details of these boundary conditions are given in Vögler (2003), and we here note only two differences we have implemented to treat pores. The first concerns the magnetic field at the upper boundary, where, as an alternative to the purely vertical magnetic field boundary condition used by Vögler, we have implemented a boundary condition where the field is matched to a potential field above the simulation box. These two boundary conditions represent limiting cases, the former case perhaps more relevant to the early stages of a pore's life, while the latter condition might be closer to the late stages of its life, after it has had time to relax. Below we compare these two limiting cases. The second change we have made concerns the fact that pores are dark because the magnetic field inhibits the transfer of energy. This process occurs naturally inside the computational domain, but its effect outside the computational domain must be modeled through the boundary conditions. We have done so by reducing the temperature of inflowing material by 15 % when the magnetic field at the bottom boundary exceeds 180 G.

Numerical simulations by Bercik (2002) and Vögler (2003) have shown that whilst the dynamics of the upper 1000 km is sufficient to account for the formation of network elements and micro-pores, it does not produce larger magnetic concentrations such as pores and sunspots. The formation of these appears to depend on processes occurring substantially deeper. Since our simulations here cover a similar height range to that in Vögler (2003), a pore will not form of its own accord. For this reason we constructed an initial condition with a plug of concentrated magnetic field, using a two-dimensional version of the code since fewer instabilities exist to break up the flux concentration in two dimensions. When the solution was approaching a quasi-stationary state we rotated the 2-D solution about the center of the pore to produce an asymmetric, three dimensional initial condition. Special attention was paid to ensure that $\nabla \cdot \mathbf{B} = 0$ was maintained.

Our study of pores is then restricted to its structure from after its formation to its decay.

3. Results

3.1. Vertical Magnetic Field Boundary Condition

The asymmetry in the initial condition is immediately broken by the fact that our domain is a set of periodic rectangular prisms rather than a cylinder, and after approximately 30 minutes the symmetry is effectively destroyed. This solution is quite stable even in three dimensions. The results shown in Fig. 1 illustrate the solution about one hour after the three-dimensional simulation was began, and the pore still clearly exists as a coherent structure in the center of the intensity image. It is surrounded by a bright rim, which corresponds to a

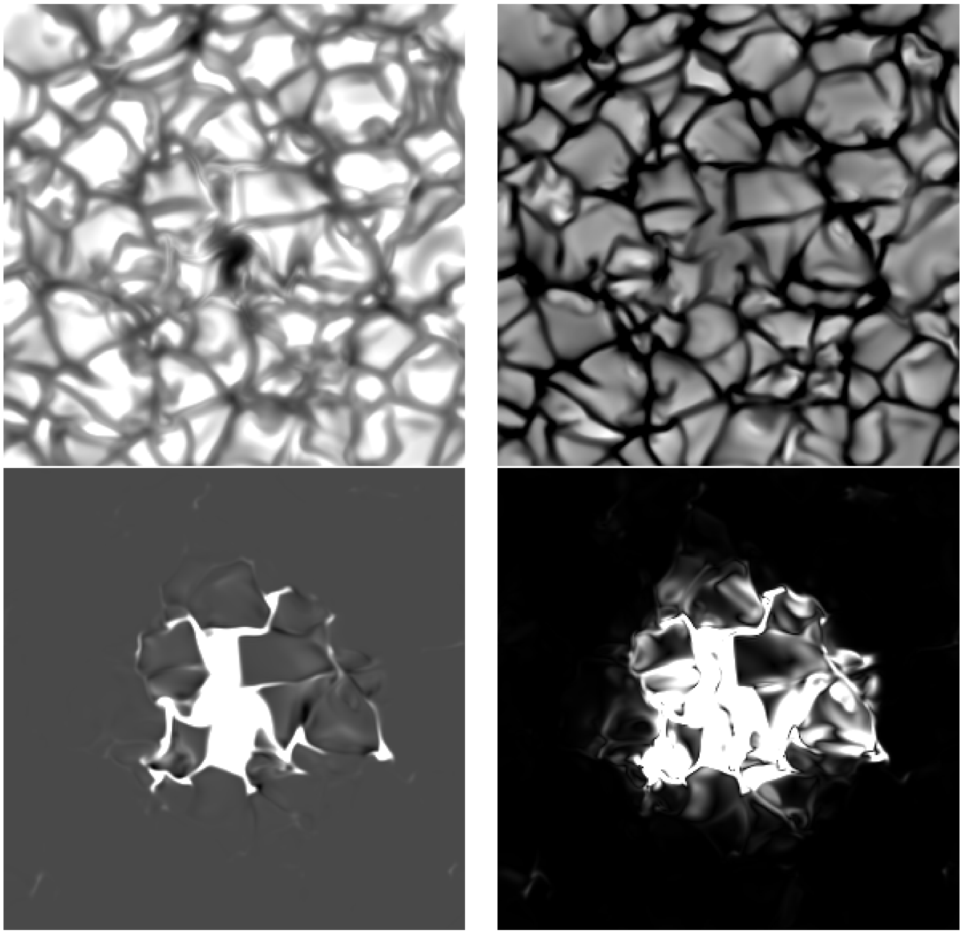

Figure 1. Results with the vertical field boundary condition. From upper left, clockwise: intensity, vertical velocity, magnitude of the horizontal magnetic field, and the vertical component of the magnetic field at $\tau = 1$. The gray-scale used for the vertical magnetic field saturates at ±1000 G, that for the horizontal field at ±100 G.

downflow surrounding the pore. This downflow is, in part, responsible for the stability of the pore in that it requires a horizontal flow of material from outside the pore in order to supply the mass involved in the downflow. This radially inward horizontal flow prevents flux from escaping the pore.

The downflow is quite weak along some of the intergranular lanes which lie perpendicular to the pore, and flux has escaped along some of these channels. At the time of this snapshot, the escaped flux has begun to form micro-pores at nearby vertexes. These micro-pores are forming in regions where the magnetic field above them is dominated by the central pore and perhaps consequently have a richer spatial structure than would otherwise be the case.

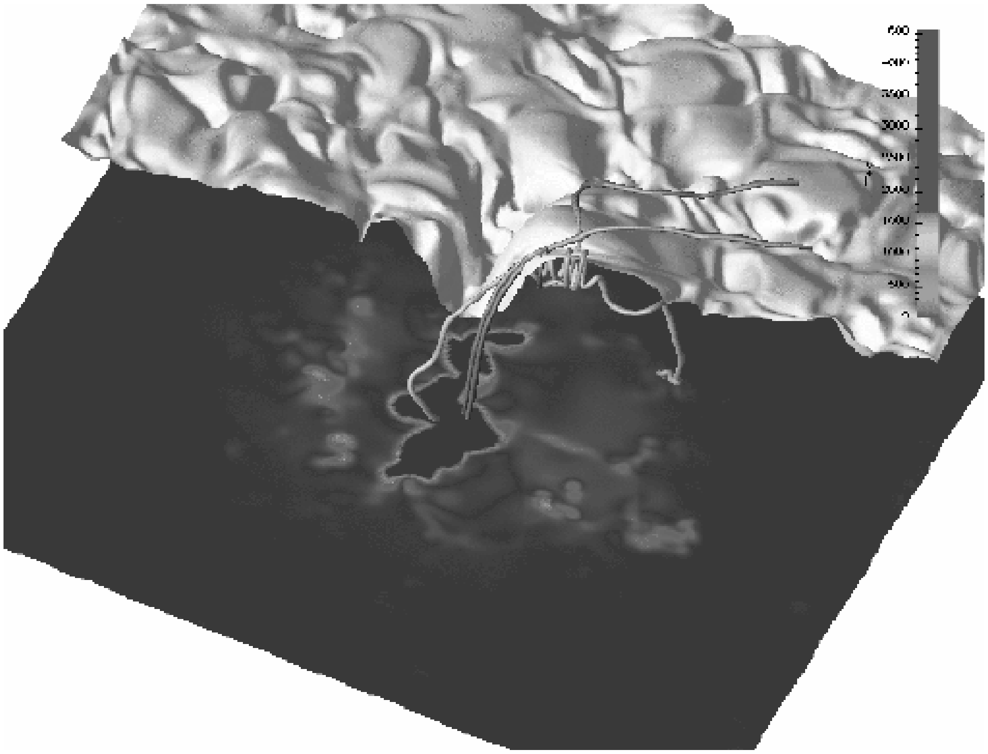

Figure 2. Result with the potential field boundary condition: (solution 10 minutes after potential field boundary condition imposed.) Shown is the $\tau = 1$ surface shaded in gray-scale according to the emergent intensity. The vertical component of the magnetic field is displayed at the bottom of the box and along two field lines. One velocity streamline is also shown (the line with several windings along its axis).

3.2. From the Potential Field Condition

Our second boundary condition matches the field at the top of the computational domain with a potential field. Since a potential field has magnetic energy almost everywhere, it follows that the magnetic field must spread out much more rapidly with height than is the case with a vertical magnetic field boundary condition. This is likely to reflect the conditions found when a pore has had a long time to equilibrate with its surroundings. It thus is an appropriate boundary condition for a pore in its old age.

The rapid expansion of the magnetic field lines with height means that the interaction of the magnetic field and the top layers of the convection is very important. Such an interaction can be seen in Fig. 2, where we show a helical streamline with several windings and two magnetic field lines, which have been distorted by the flow.

An examination of the temperature structure (not shown) demonstrates that this is a convective effect, driven by a large temperature gradient just below the surface. Comparing the magnetic and kinetic energy densities in this region shows that it is a magnetoconvective effect. We comment that this type

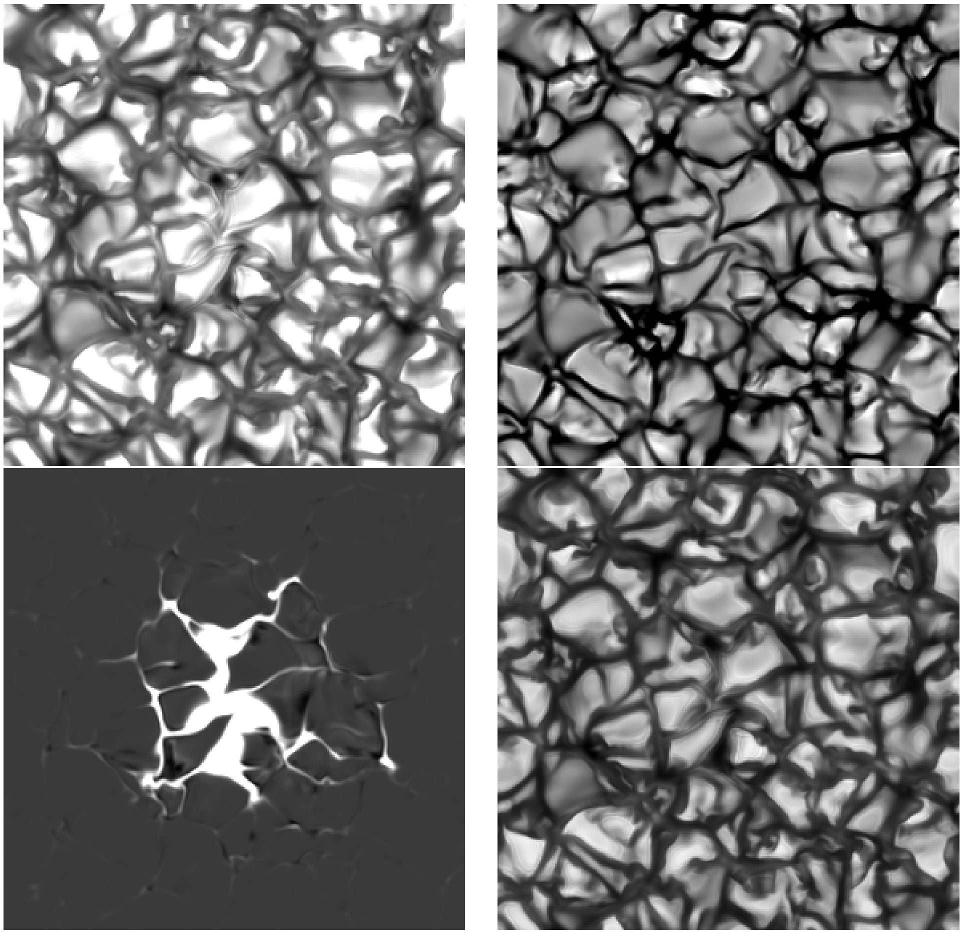

Figure 3. Results with the potential field boundary condition: From upper left, clockwise: intensity, vertical velocity, line-integrated image from G-band wavelengths, and vertical magnetic field. The vertical velocity and magnetic field correspond to the $\tau = 1$ surface.

of convective roll is at least superficially similar to that which has been discussed in the context of the penumbra by, for example, Danielson (1961).

Perhaps because of the enhanced interaction with the convective motions, the pore was much less stable with the potential field boundary condition. To make possible a comparison between the boundary conditions, we took the solution with the purely vertical boundary condition at about 45 minutes of simulation time, and ran it for an additional 15 minutes with the potential field boundary condition. The result is shown in Fig. 3, which is then at the same time as Fig. 1. The pore in Fig. 3 no longer has a coherent dark structure in the center of the intensity image, but appears to have split. Similarly the structure of the downflow is more complicated, and the growth of the micro-pores more advanced. The pore is indeed near the end of its life as a pore. The lifetime of the pore after the imposition of this boundary condition is quite short, however this might be partially because this is quite a small pore.

4. Discussion

This paper has restricted itself to a qualitative examination of the features of our simulated pore and its decay. The shallow magneto-convective roles are an interesting effect of the interaction between a rapidly diverging magnetic field and the top layers of the convective zone. It is a feature where all the various effects included in the simulation are of a similar importance, and is quite complicated in detail. Its observational signature is yet to be explored.

Another interesting finding concerns the differences in the pores lifetime with the two boundary conditions. This effect invites further investigation on pores of different sizes, and we are currently performing a series of computations to study pores of different sizes and have began a quantitative comparison between the simulations and observations.

Lastly, and largely unrelated to the main points of this article, we comment that the convective rolls as described above are the type of source of torsional Alfvén waves that were favored by Professor Uchida. We believe their demonstration here would have added to his broad and infectious smile.

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