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Compressible magnetoconvection as the local producer of solar-type magnetic structures

W. Dobler[1]† and A. V. Getling[2]

[1] Kiepenheuer-Institut für Sonnenphysik, Schöneckstrasse 6, 79104 Freiburg, Germany

[2] Institute of Nuclear Physics, Lomonosov Moscow State University, 119992 Moscow, Russia, email: A.Getling@ru.net

Abstract. Simulations of cellular magnetoconvection in a compressible fluid reveal the formation of magnetic structures with a substantial bipolar component as an inherent property of the topology of cellular flows.

Numerical simulations of magnetoconvection have mostly been focused on such issues as the spatial separation of the flow and magnetic flux, oscillations and waves associated with magnetoconvection in a compressible fluid, or a "realistic" description of magnetic flux tubes in turbulent solar plasma (for very small computational domains). In contrast, little attention has been given to the possible role of cellular convection in amplifying and structuring photospheric magnetic fields, although such effects were demonstrated very long ago by Tverskoy (1966) based on a simple kinematic model. Recently Getling (2001) and Getling & Ovchinnikov (2002) simulated them numerically in the Boussinesq approximation. Here, we study cellular magnetoconvection in a compressible fluid.

To simulate magnetoconvection in a plane horizontal fluid layer $0 < z < h$ heated from below, we use the finite-difference *Pencil Code* (Brandenburg & Dobler 2001). The stress-free horizontal boundaries of the layer have infinite thermal and electric conductivities. Initially (at $t = 0$), a polytropic stratification is superposed with a weak thermal perturbation in the form of a spatially periodic pattern of hexagonal, Bénard-type convection cells. Their size is equal to that at the onset of convection in a Boussinesq fluid.

The uniform initial magnetic field $\mathbf{B}_0$ is either horizontal or inclined by 45°. At a hydrodynamic Prandtl number of $P_1 = 1$, we explored the following parameter ranges: $R = 2000$–$20\,000$ for the Rayleigh number, $P_2 = 1.5$–30 for the magnetic Prandtl number, and $Q = 0.1$–10 for the Chandrasekhar number. We also varied $\Delta T/\overline{T}$ (where ΔT is the temperature difference across the layer and $\overline{T}$ is the mean temperature). Throughout these ranges, the magnetic structures produced by convection are largely similar. This is evidence for the decisive role of the flow topology in the formation of these structures.

By the time when the velocity field $\mathbf{u}$ and the magnetic field $\mathbf{B}$ become quasi-steady, $\mathbf{B}$ is strongly amplified and has a mainly bipolar structure superposed with finer details (see Fig. 1 for a run started from a horizontal $\mathbf{B}_0$). In addition, sweeping of the magnetic flux toward the cell boundaries is observed. Another remarkable effect is the "topological pumping" of the horizontal magnetic field (Drobyshevski & Yuferev 1974): as Fig. 1d shows, an intense horizontal magnetic flux is accumulated at the bottom of the layer.

Eventually, hexagonal cells transform into convection rolls, after which the amplified component of the magnetic field decays. However, at high P_2 (~ 30), the magnetic field reaches its absolute maximum during the breakdown of the cells. This occurs because the flow produces local compressions of the remnants of the previously regular field.

† Present address: Department of Physics and Astronomy, University of Calgary, 2500 University Drive N.W., T2N 1N4 Calgary, Alberta, Canada

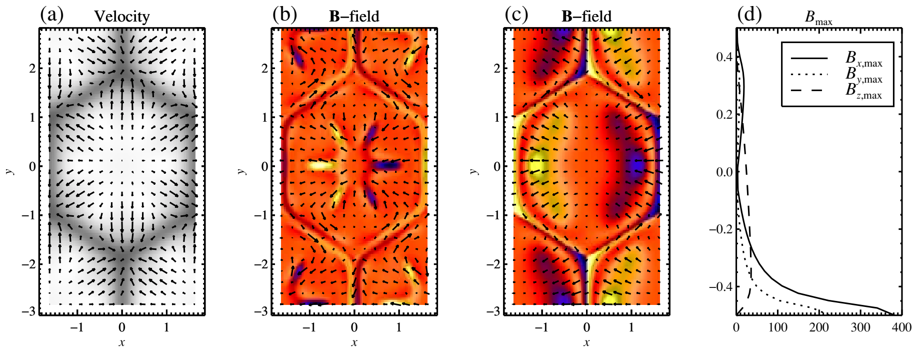

Figure 1. Solution for a horizontal $\mathbf{B}_0$, $R = 5 \times 10^3$, $P_1 = 1$, $P_2 = 30$, $Q = 1$, and $\Delta T/\overline{T} = 0.83$ at $t = 40\sqrt{h/g}$: (a) $\mathbf{u}$ at $z/h = 0.487$; (b, c) $\mathbf{B}$ at $z/h = 0.066$ and 0.487, respectively (light for positive and dark for negative values of the z components, arrows for the horizontal components); and (d) z distribution of the maximum values of B_x, B_y, and B_z (in units of B_0).

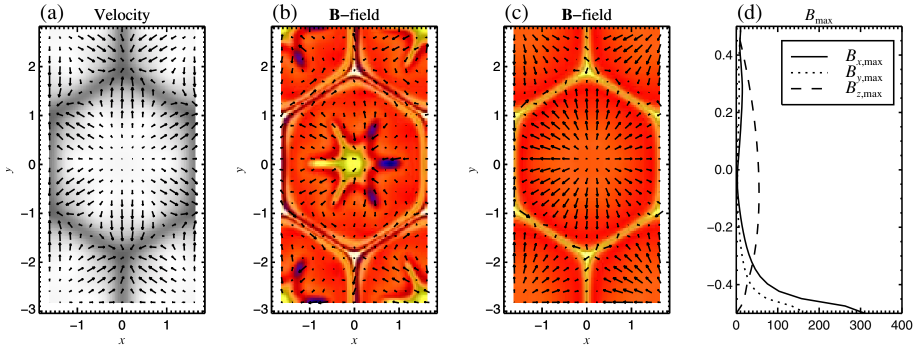

Figure 2. Same as in Fig. 1 but for a $\mathbf{B}_0$ inclined by 45° to the horizontal plane.

If the initial magnetic field is inclined (Fig. 2), a similar evolution is observed but a strong unipolar concentration of magnetic flux is present in the amplified field. Near the midheight in the layer, this is manifest in a substantial asymmetry of polarities.

Thus, cellular magnetoconvection in a horizontal layer of compressible fluid exhibits the fairly stable property of producing specific structures of strongly amplified magnetic field. They closely resemble solar magnetic regions, being generally a superposition of a bipolar and unipolar configurations mixed in a proportion that depends on the inclination of the initial magnetic field to the horizontal plane. The mechanism described here is an alternative to the widely known rising-tube model and seems very promising in terms of better compatibility with observations.

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