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CELLULAR COMPRESSIBLE MAGNETOCONVECTION: A MECHANISM FOR MAGNETIC-FIELD AMPLIFICATION AND STRUCTURING

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Summary The amplification and structuring of magnetic field by cellular compressible magnetoconvection is studied using numerical simulations. The cases of both horizontal and inclined initial magnetic fields are considered. Magnetic structures with a substantial bipolar component (typical of solar magnetic regions) are produced, and their development seems to be inherent in the very topology of the cellular convective flow. If the initial field is inclined, a compact unipolar concentration of magnetic flux is also present. These new effects are complemented with the well-studied sweep of the vertical magnetic field to the cell boundaries and with a strong concentration of the horizontal magnetic field near the bottom boundary of the layer (so-called topological pumping).

INTRODUCTION

Numerical simulations of magnetoconvection are largely motivated by problems of solar physics. Most investigators (M.R.E. Proctor, N.O. Weiss, Å. Nordlund, R. Stein, F. Cattaneo, and others) have concentrated 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 the evolution of magnetic flux tubes in a turbulent medium under conditions similar to solar ones (which is only possible for very small computational domains). In contrast, little attention has been given to the role of cellular magnetoconvection in amplifying and structuring magnetic fields, although the possibility of such effects was demonstrated by Tverskoy (based on a simple kinematic model) as long ago as in 1966 [1]. Meanwhile, the properties of a convection cell as the producer of specific, "solar" configurations of the amplified magnetic field are of paramount importance in the context of comprehending the origin of local magnetic fields on the Sun — an important ingredient of solar activity.

We present here the first results of our study of magnetoconvection in a compressible fluid and demonstrate the formation of localized structures of the strongly amplified magnetic field to be an inherent property of the cellular flow topology; some results concerning the effects under discussion were previously obtained in a Boussinesq approximation using spectral simulations [2, 3].

THE PROBLEM AND SIMULATION TECHNIQUE

We consider a plane horizontal fluid layer $0 < z < h$ heated from below. The dynamics of the flow and magnetic field is described by the standard system of equations, which includes the equation of motion, the continuity equation, the energy-transfer equation written in terms of entropy, and the induction equation. We assume that the bottom and top boundaries of the layer have infinite thermal and electric conductivities, so that the temperature is fixed, normal velocity and normal magnetic field are zero at these boundaries, while the tangential stresses and the tangential electric current vanish there. As initial state, we choose a superposition of a polytropic stratification and a weak thermal perturbation in the form of a spatially periodic pattern of hexagonal, Bénard-type convection cells. The horizontal wavenumber of this perturbation is equal to the critical value for the onset of convection in a Boussinesq fluid, $k_\mathrm{c} = \pi/\sqrt{2}h = 2.22/h$.

For our simulations, we use the Pencil Code developed by Brandenburg and Dobler [5]. This is a cache-efficient, high-order finite-difference code (sixth order in space and third order in time) that solves the compressible magnetohydrodynamic equations. The computations are restricted to a rectangular box $3.27 \times 5.66 \times 1$ with periodic boundary conditions at the side boundaries, and the grid typically contains $138 \times 240 \times 41$ points.

The layer depth h, the gravitational acceleration g, and the quantity $\sqrt{h/g}$ are used as the units of length, acceleration, and time, respectively. The mean gas density $\overline{\rho}$ is set to unity, which specifies the unit of mass. The unit magnetic field corresponds to a nondimensional Alfvén speed of unity. For any run, we specify the kinematic viscosity ν, the mean thermal diffusivity $\chi = \lambda/\overline{\rho}c_p$ (where λ is the thermal conductivity and c_p is the specific heat at constant pressure), the magnetic viscosity ν_m, the initial magnetic field B_0, and the ratio $\Delta T/\overline{T}$ (where ΔT is the temperature difference between the bottom and top boundaries and $\overline{T}$ is the mean temperature).

The initial magnetic field $\mathbf{B}_0$ is uniform and either directed along the x axis or inclined to it by 45°. The input quantities map to the usual nondimensional parameters of the problem,

$$R = \frac{g\,h^3(\Delta T - g/c_p)}{\nu\chi\overline{T}}, \quad Q = \frac{B_0^2 h^2}{\mu_0\overline{\rho}\nu\nu_\mathrm{m}}, \quad P_1 = \frac{\nu}{\chi}, \quad P_2 = \frac{\nu}{\nu_\mathrm{m}}$$

(where μ_0 is the vacuum permeability), called the Rayleigh number, the Chandrasekhar number, the hydrodynamic Prandtl number, and the magnetic Prandtl number.

RESULTS

We kept $P_1 = 1$ and varied R from 2000 to 20 000, P_2 from 1.5 to 30, and Q from 0.1 to 10. In addition, we varied the compressibility of the fluid. Throughout this region of parameter space, the magnetic structures produced by convection were largely similar. This is evidence for the decisive role of the flow topology in the formation of these structures.

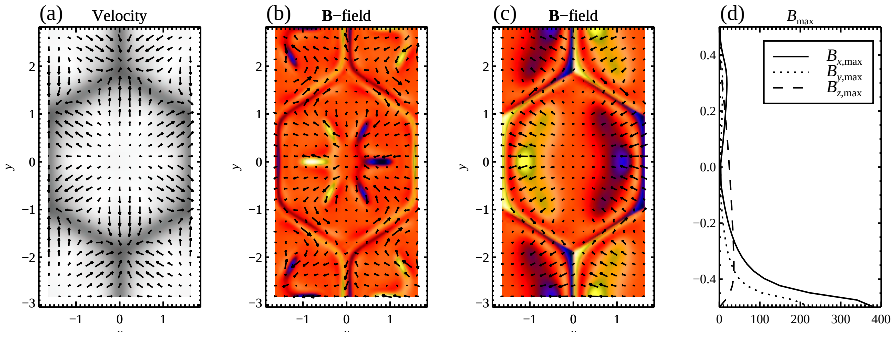

Figure 1. Simulation results for the case of a horizontal initial magnetic field, $R = 5 \times 10^3$, $P_1 = 1$, $P_2 = 30$, $Q = 1$, $\Delta T/\overline{T} = 0.83$, and time $t = 40$: (a) velocity field in the plane $z/h = 0.487$; (b, c) magnetic field in the planes $z/h = 0.066$ and 0.487, respectively (light for positive and dark for negative values of the vertical component, arrows for the horizontal components); and (d) the vertical distribution of the maximum values of all three magnetic-field components (expressed in units of the initial field B_0).

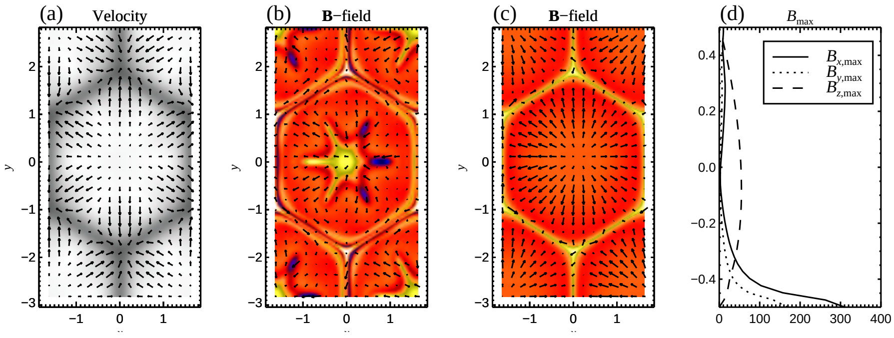

Figure 2. Same as in Fig. 1 but for an initial magnetic field inclined by 45° to the horizontal direction.

At an early stage of the process, decaying acoustic oscillations accompany a steady growth in the amplitudes of the velocity and magnetic field (which grows mainly kinematically). After this linear stage, the flow settles down to a nearly steady state, and the strongly amplified magnetic field also varies little during some time interval. It has now a mainly bipolar structure superposed with finer details. Figure 1 illustrates a well-developed magnetic structure of this type obtained in a run started from a horizontal initial magnetic field. (Except these new features, sweeping of the magnetic flux toward the cell boundaries is observed. Another remarkable effect is the “topological pumping” of the horizontal magnetic field [5]: as Fig. 1d indicates, an intense horizontal magnetic flux is accumulated near the bottom of the layer.)

Subsequently, a transition from the hexagonal cells to a roll flow occurs, which ultimately results in the decay of the amplified component of the magnetic field. However, at high magnetic Prandtl numbers ($P_2 = 30$), the magnetic-field strength reaches its absolute maximum only during the breakdown of the cellular flow. This occurs since the relatively disordered remnants of the previously regular, amplified field experience local compressions by the flow.

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

CONCLUSION

We have shown that cellular magnetoconvection in a horizontal layer of compressible fluid can act as an efficient mechanism of magnetic-field amplification and structuring. It exhibits the fairly stable property of producing specific patterns of strongly amplified magnetic field, and they do not change their qualitative features over a fairly wide region in parameter space. Such a magnetic structure is generally a superposition of a bipolar and a unipolar configuration mixed in a proportion that depends on the inclination of the initial magnetic field to the horizontal plane. Magnetic patterns of this type closely resemble solar magnetic regions. The mechanism described here is an alternative to the rising-tube model widely known in solar physics and seems very promising in terms of better compatibility with observations.

References

[1] Tverskoy B.A.: A Contribution to the Theory of Hydrodynamic Self-Excitation of Regular Magnetic Fields. *Geomagn. Aeron.* **6**:11–18, 1966.
[2] Getling A.V.: Convective Mechanism for the Formation of Photospheric Magnetic Fields. *Astron. Zh.* **45**:661,2001 (Engl. transl.: *Astron. Rep.* **45**:569, 2001).
[3] Getling A.V., Ovchinnikov I.L.: Solar Convection as the Producer of Magnetic Bipoles. *Proc. 10th European Solar Physics Meeting, “Solar Variability: From Core to Outer Frontiers,” Prague, Czech Republic, 9–14 September 2002 (ESA SP-506, December 2002)*, pp. 819–822.
[4] Brandenburg A., Dobler W.: http://www.nordita.dk/data/brandenb/pencil-code
[5] Drobyshevski E.M., Yuferev V.S.: Topological Pumping of Magnetic Flux by Three-Dimensional Convection. *J. Fluid. Mech.* **65**:33–44, 1974.

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