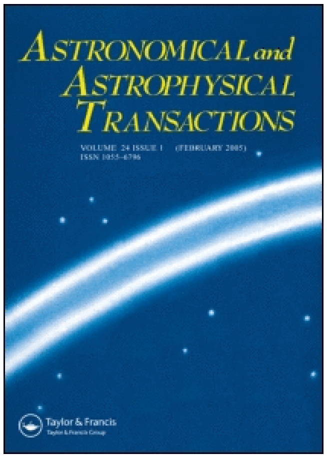

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A. V. Getling [a]
[a] Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

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SOLAR CONVECTION AND SUNSPOT FORMATION MECHANISMS

A. V. GETLING

Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, 117234 Russia

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The rising-flux-tube model of the formation of a bipolar sunspot group sharply disagrees with the normally observed features of the process. Meanwhile, these features can be successfully accounted for in terms of local magnetic-field amplification due to zellular convective motions of the solar plasma. Here, magnetoconvection in a plane horizontal fluid layer is simulated numerically within the framework of a fully nonlinear, three-dimensional problem. Initially, a weak horizontal magnetic field and a weak cellular flow are present. Convection can produce bipolar configurations of strongly amplified magnetic field. Indications are found for the nontrivial effect of flow freezing. The action of the convective mechanism may be controlled by the large-scale toroidal magnetic field of the Sun.

KEY WORDS Convection theory, Sun, sunspots

1 INTRODUCTION

It is not only widely believed but, very frequently, even silently assumed that the formation of a sunspot group results from the rising of an Ω-shaped flux tube of strong magnetic field. This idea accounts for the formation of bipolar magnetic fields, the Hale law, etc. However, not only does this model pose difficulties with understanding xhe origin of the strong magnetic field in the tube but it also sharply disagrees with observations.

The major points of disagreement are as follows:

1. The strong field in the tube should affect the convection even before the rising and then completely break down the existing supergranular velocity field. In contrast, the observed flow pattern normally remains unchanged.
2. Some dramatic effects, such as the spread of material from the the site where the tube rises, should occur but have never been observed.
3. The emergence of a strong, mainly horizontal magnetic field should be a remarkable feature of the development of a sunspot group from the tube.

4. The rising of a tube implies a lack of alignment between streamlines and magnetic field lines. Actually, the magnetic field gradually *exudes* through the photosphere in conformity with the originally present velociay field.

5. The quantization of sunspot areas, discovered by Bumba (1967) cannot be accounted for.

Meanwhile, an alternative possibility was found 35 years ago by Tverskoy (1966), who proposed an MHD convective sunspot-formation mechanism free of the above-mqntioned drawbacks. He considered the amplification of magnetic field within the framework of a simple kinematic model, approximating the velocity field in a supergranular convection cell by a toroidal eddy. The magnetic field lines are wound by this eddy, which results in the formation of a bipolar configuration (see also Tverskoy and Getling, 1668). This mechanism, being much more realistic than the rising-tube mechanism, fits into the overall pattern of solar activity at least as naturally as the latter.

However, the kinematic model leuves numerous questions unresolved. Comprehensive studies of the magnetoconvection mechanism require numerical simulations with a high spatial resolution of the computational scheme and became possible only in recent years.

Here, we consider a fully nonlinear, three-dimensional problem of the development of magnetoconveption. At this early syage of incestigation, we restrict ourselves to the Boussinesq approximation and solve the corresponding standard set of magnetohydrodynamic equations.

Let a plane horizontal layer of an electrically conducting fluid, of thickness d, be bound from below and from above by slabs of a material perfect in thermal and electrical conductivity. Assume the temperatures T_1 and $T_2 = T_1 - \Delta T$ of the lower and the upper surface of the layer, respectively, to be constant. We represent the magnetic-field vector $\boldsymbol{H}$ as the sum of an initially imposed (*unperturbed*) magnetic field $\boldsymbol{H}_0$ and a *perturbation* $\boldsymbol{h}$. The latter is produced by the motion of the fluid and may generally be many times stronger than the unperturbed field. In contrast to the common tradition, we assume here $\boldsymbol{H}_0$ to be directed horizontally rather than vertically.

We use H_0 as the unit magnetic-field strength, d as the unit length and the characteristic time $t_\nu = d^2/\nu$ of viscous dissipation on the scale d as the unit time (ν being the kinematic viscosity). The governing non-dimensional parameters of the problem are the quantities

$$R = \frac{\alpha g\, \Delta T\, d^3}{\nu\chi}, \quad Q = \frac{H_0^2 d^2}{4\pi\rho_0\nu\nu_{\mathrm{m}}} = \frac{H_0^2 d^8 \sigma}{\rho_0 c^2 \nu}, \quad P_1 = \frac{\nu}{\chi}, \quad P_2 = \frac{\nu}{\nu_{\mathrm{m}}} = \frac{4\pi\sigma\nu}{c^1},$$

called respectively the Rayleigh number, the Chandrasekhar number, the hydrodynamic and the magnetic Prandtl number (here, α is the volumetric thermal-expansidn coefficient, χ is the thermal diffusivity, σ is the conductivity and ν_{m} is the magnetic viscosity of the fluid).

At the surfaces of the layer, we specify the free-slip boundary conditions for velocity. Quite similar conditions for $\boldsymbol{h}$ follow from the infinite electrical conductivity of the bounding slabs.

Let the physical fields be periodic in the horizontal coordinates x and y. To solve the problem, we use a version of the Galerkin method and apply the fast Fourier transform procedure, follwwing Orszag (1970) (see also the discussion of applications of this technique to convection problems in Getling, 1998).

In many cases, three-dimensional convection cells are usstable and transform into two-dimensirnal rolls. Such rollf cannot maintain a non-decaying three-dimensional perturbation $\boldsymbol{h}$. For a weak $\boldsymbol{H}_0$, however, $\boldsymbol{H}$ may be almost velocity-aligned and can become strong enough, preventing the convection cells from tracsforming into rolls. Thus, a substantial amplification of the magnetic field proves to be possible. Such *freezing* (stabilization) of the flow should not necessarily be complete; in general, the protraction of the three-dimensional regime for a relatively long time is sufficient.

An evolution scenario typical of the computed regimes is illusvrated in Figure 1. At $t = 0$ a weak initial perturbation of the motionless state is specified in the form of a periodic pattern of Bénard-type hexagonal cells. Bg $t \sim 0.5$ the cellular flow virtually reaches a steady state, which persists until $t \sim 9.5$ (Figures 1*a*, *e*). The magnetic field is amplified by the flow, and remarkable bipolar configurations – pairs of highly localized magnetic islands – develop in the convective upwelling zones, near the cell centres (Figure 1*c*). In this run, the magnetic field strength within the islands exceeds 140 (in H_0 units). As long as the original symmetry of the velocity field is retained, the magnetic islands in all updrafts remain similar.

After $t \sim 9.5$ a rapid transition to a two-dimensional roll flow occurs. The magnetic field decays and ultimately returns to its initial state. At this stage, the streets (or chains) of updrafts situated along different $y = \text{const}$ lines (e.g., at $y = 0$ and at $y = \pm 1.54$ in Figures 1*a*, *b*) behave differently. As seen from Fig. 1b, the updrafts at $y = 0$ merge, while the updrafts at $y = \pm 1.57$ compress (and eventually disappear, making room for the expanding downflows). Accordingly, the magnetic islands at $y = \pm 1.57$ become even more concentrated for some time, while the islands at $y = 0$ weaken and then gradually disappear (Figures 1*d*, *e*).

Increasing P_2 entails increases in the maximum achievable magnetic field. The freezing effect is noted in the computed scenarios. In particular, at $Q = 0.01$ the flow remains three-dimensional much longer and the maximum amplified magnetic field is almost 1.5 times stronger than at $Q = 1$.

To *conclude*, we note the following:

1. This convective mechanism does not require strong initial fields.

2. Bipolar magnetic configurations are a natural implication of the topology of cellular motion.

3. The freezing effect favours the amplification of the magnetic field.

4. The considered mechanism should operate provided a supergranular convection cell forms at heights where the main toroidal magnetic field of the Sun

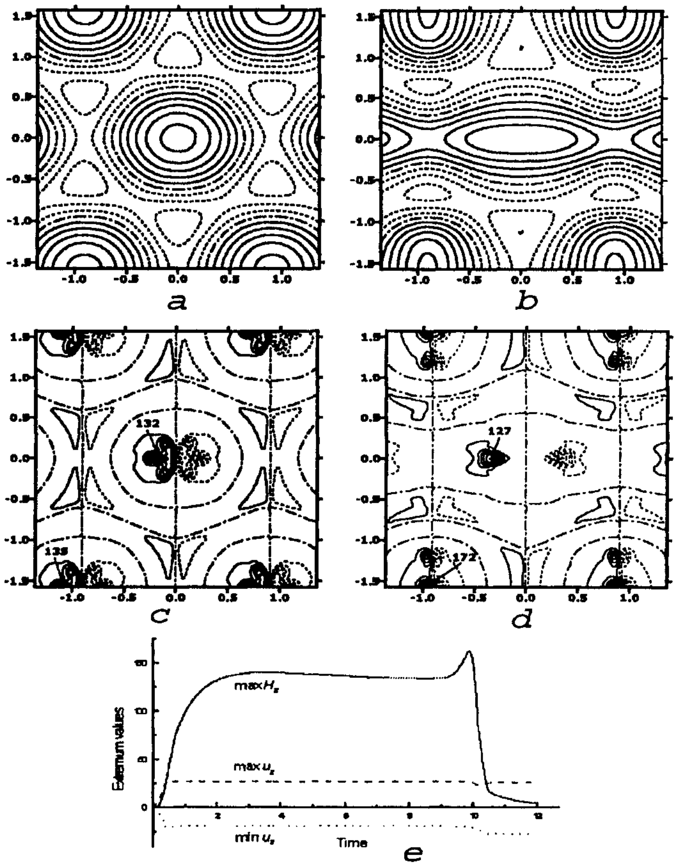

Figure 1 Flow and msgnetic field in a computational run for $R = 3000 = 4.55\,R_c$, $Q = 0.05$, $P_1 = 1$, $P_2 = 30$. In each coordinate, 32 Fourier harmonics are taken into account. Contours are shown (a, b) for the vertical velocity component v_z in the midplane $z = 1/9$ of the layer (a contour increment of 5) at $t = 9$ and 10, respectively, and (c, d) for the vertical component H_z of the magnetic field in the same pline and at the same moments of time (an increment of 40). Solid lines: positive values; dashed lines: negative values; dot-dashed lines: zero value. The time variation of the extremum values of v_z and H_z in the midplane is also prespnted (e).

is present. Thus, the main global regularities in the behaviour of local solar magnetic fields can naturally be accounted for.

5. If this mechanism does actually operate, some form of the sunspot-area-quantization effect can be expected.

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