NUMERICAL 3-D SIMULATIONS OF THE COLLAPSE OF PHOTOSPHERIC FLUX TUBES

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The interaction of photospheric granular convection with a small scale magnetic field has been simulated numerically in a three-dimensional model, with an extension of techniques recently used to simulate field-free granulation. The evolution of an initially homogeneous magnetic field was followed numerically, both in a kinematic (weak-field limit) description, and in a dynamic description, where the back-reaction of the field on the motion through the Lorentz force is taken into account. The simulations illustrate the strong tendency for the field to be swept up and concentrated in the inter-granular lanes because of the topology of the granular flow. The convectively unstable stratification allows field concentration up to a kilogauss field because the temperature reduction in the magnetic plasma.

1. INTRODUCTION.

As pointed out by Parker many years ago (Parker, 1955), a simple explanation for the observed concentration of magnetic flux in the solar photosphere is provided by a reduced temperature of the magnetic plasma, with a resulting lower internal gas pressure following from (almost) hydrostatic equilibrium.

Similar explanations have been given by Spruit (1976, 1977, 1979) and others (Parker, 1978; Webb and Roberts, 1978) for the concentration of magnetic field to kilogauss strength on a small scale, as first evidenced by indirect observational methods (cf. Stenflo, 1977). Spruit (1979) showed that, for an initially homogeneous magnetic field of sufficient strength, a convectively driven instability may concentrate the field up to strengths corresponding to the external gas pressure, by "evacuation" of the interior of

J. O. Stenflo (ed.), Solar and Magnetic Fields: Origins and Coronal Effects, 79–83.

the magnetic flux concentrations. A large number of other explanations for the field concentration have also been proposed (cf. Parker, 1979 and referencs cited therein). The purpose of the work reported here is to demonstrate, by numerical simulation of the actual situation, that the convective instability is indeed responsible for the concentration of magnetic flux on a small scale in the solar photosphere. This is done by an extension of techniques recently used to simulate field-free convection in the solar photosphere (Nordlund, 1982).

2. NUMERICAL CONSIDERATIONS.

Relatively little extra numerical effort (some 15 %) is required to step the full set of MHD equations forward in time, given the effort of stepping the equations of ordinary hydrodynamics. The induction equation determines the evolution of the magnetic field density $\underline{B}$, in terms of the rotation of the electric field $\underline{E}$,

$$\partial \underline{B}/\partial t = -\mathrm{rot}\underline{E} \quad .$$

The induction equation ensures that an initially divergence free magnetic field stays divergence free, since the divergence of a rotation vanishes. Numerically, this holds true if and only if the space derivatives in the div and rot operators commute. For the horizontal variations, this is automatically the case, because of the Fourier representation of the horizontal variations. For the vertical variations, which are represented by cubic splines, commutation is ensured by defining second derivatives by a similar cubic spline representation of the first derivatives.

In the equation of motion, the Lorentz force term $\underline{i}\mathrm{x}\underline{B}$ has to be included. This requires one rot operation and one vector product operation. It should be noted that the common expansion of the Lorentz force in terms of a pressure and a tension term is unfavourable in terms of numerical effort.

3. THE KINEMATIC CASE.

In the kinematic case, the ordinary equations of hydrodynamics alone determine the evolution of the temperature, pressure, and velocity, and the induction equation just describes the evolution of the magnetic field with a given velocity field.

The initially homogeneous and vertical magnetic field is carried along by the horizontal flow from the granules

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towards the inter-granular lanes. Since typical horizontal velocities are 4-6 kms^{-1} and typical granular radii are 500-1000 km, field lines are carried into the intergranular lanes in a few minutes time. Below the surface, the flow is mostly vertical, and in the shape of "fingers" of descending gas. This topology favours the concentration of field lines in the downdrafts, in contrast to situations with little or no stratification, where up/down symmetric cells may form (Galloway and Moore, 1979)

In the kinematic case, there is nothing to stop the field from concentrating without limit. In a numerical description of the evolution, the field must not be allowed to concentrate to a smaller scale than the resolution element. Therefore, a diffusion term has to be included in the induction equation (resistive term in $\underline{E}$), of a magnitude sufficient to prevent excessive concentration. On the other hand, in order for the dynamic case to be realistic, diffusion must not prevent concentration before the Lorentz force becomes dominant in the equation of motion. Taken together, these two conditions imply a minimum total flux in the model determined by the numerical resolution; the higher the numerical resolution, the smaller total flux may be allowed, with small scale flux concentrations still reaching sufficient flux density. In the case considerd here, with a horizontal period of 3000x3000 km, and 256 Fourier components in the plane, an initial flux density of 35 mT (350 Gauss) was found suitable.

4. THE DYNAMICAL CASE.

When the Lorentz force is included in the equaion of motion, the concentration of magnetic flux in the intergranular lanes is retarded by the Lorentz force, directed away from the flux concentrations (magnetic pressure term in the pressure plus tension expansion). However, the retarded flow results in a smaller supply of entropy to the intergranular lanes by the flow. The layers where the radiative continuum is formed are losing entropy at a significant rate. The reduced horizontal inflow therefore results in a further reduced temperature of the descending gas. The reduced temperature corresponds to a reduced gas pressure scale height, and consequently the gas pressure in the intergranular lanes is reduced further, relative to the case of field-free convection. This offsets the retardation by the Lorentz force and allows further concentration of the magnetic flux. A (quasi-) stable situation is reached when the internal gas pressure is well below the external gas pressure, because then further reductions of the internal gas pressure have only marginal effects on the external-internal gas pressure difference. In this situation, the magnetic flux is concentrated in the intergranular lanes, with almost field-free plasma in the granular updrafts. The flow in these field-free areas evolves in a way typical of normal (field-free) granular convection; the granules grow and then split (or "explode"), because the central updraft eventually reverses, after radiative cooling overtakes the stagnating upflow. Thus, new downdrafts form in the field free areas. The magnetic flux expands horizontally into these newly formed downdrafts, because the external gas pressure in the downdrafts are insufficient to balance the internal magnetic pressure of the flux concentrations.

5. DISCUSSION, CONCLUSIONS.

The numerical simulations reported here illustrate the mechanisms responsible for the formation of small-scale magnetic flux concentrations in the solar photosphere: The topology of the granular flow is such that magnetic field is carried towards the intergranular lanes, and the heat cycle of the convective flow is such that it aids in the concentration of the field up to flux densities where the field is essentially confined by the external gas pressure of the field free fluid.

However, these flux concentrations are not stationary; the magnetic field continually readjusts in response to the evolution of granules in the field-free areas. In a certain sence, the lifetimes of the flux concentrations are thus of the order of the granular life times, even though no flux is destroyed. The stresses (shear, twist) caused by this continual readjustment propagate up into the chromosphere and the corona, along the fieldlines rooted in the photosphere. To the extent that Alfven transit times are short compared to characteristic times of evolution (short loops), the field in the corona will evolve through a series of (almost) force-free states. The magnetic field aligned currents associated with such twisted fields may cause resistive MHD instabilities similar to Tokamak instabilities (Waddell et al. 1979, Carreras et al. 1980), and may thus be of importance for the small scale chromospheric and coronal activity.

The video-tape sequence illustrating this contribution was produced with a MATROX RGB-256 frame buffer, mounted on a PDP 11/35 computer. The financial support of the Danish Space Board and the Danish Natural Science Research Council, and the access to the Niels Bohr Institute PDP 11/35 is gratefully acknowledged.

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DISCUSSION

PROCTOR: Did you include diffusion in the model? Presumably it is essential for a steady state to be established. Does the value of the diffusion coefficient affect the final state?

NORDLUND: Yes, as explained in the text of my contribution, diffusion is necessary to prevent the flux from concentrating below the limit of numerical resolution. The value of the diffusion coefficient does not qualitatively affect the final state, since the initial value of the vertical field was chosen large enough to make the Lorentz force dominate before diffusion does. In other words, the flux density reaches values of several hundred mT in the kinematic case, whereas pressure balance limits the flux density to some 150 mT in the dynamic case. However, the value of the diffusion coefficient does influence the amount of downflow in the flux concentrations, because it determines the amount of cross-field flow allowed.

KÖMLE: Which numerical code did you use for your calculations?

NORDLUND: An extension of the pseudo-spectral code used for numerical simulation of field-free granular convection, as described in *Astron. Astrophys.* **107**, p. 1, 1982.

ROSNER: Is your code fully compressible? Furthermore, what is your grid spacing compared with the pressure or density scale height?

NORDLUND: The code is compressible, in the sense that the model extends over ten pressure scale heights. However, the $\partial\rho/\partial t$ in the continuity equation is neglected, which has the effect of filtering out sound waves (and fast-mode waves). The numerical resolution used was: Horizontally 3000 km/16 points $\approx$ 190 km, vertically $\approx$ 50 km.

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