CONVECTIVE COLLAPSE AND OVERSTABLE OSCILLATIONS IN SOLAR FLUX TUBES

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ABSTRACT

The collapse of solar flux tubes by a convective instability is investigated. At the initial epoch it is assumed that the flux tube is in hydrostatic equilibrium and that it has the same temperature as the ambient medium. The superadiabatic stratification in the tube drives a convective instability. If the initial equilibrium is perturbed by the introduction of a small downflow in the tube, convective collapse occurs leading to magnetic field intensification. The final state consists of overstable oscillations with periods typically around 1000s. It is found that the surface magnetic field is in the observed 1-2 kG range. Moreover, there is an oscillating flow (unidirectional at any instant) with an amplitude 1-2 km/s and an average value around zero.

Keywords: convection, hydromagnetics, flux tubes, Sun, magnetic fields, flows

1. INTRODUCTION

Photospheric observations of the Sun have established that the magnetic field is concentrated into flux tubes with field strengths in the range 1-2 kG. It has been suggested that downflows are associated with these tubes (Refs. 2-3) although there appears to be some doubt regarding the nature of these downflows (Ref. 8). The absence of a net displacement in the zero crossings between the V and I profiles (Ref. 8) appears to rule out a continuous downflow.

Theoretically, the mechanism that produces intense flux tubes on the Sun is not firmly established. The present investigation quantitatively examines the hypothesis first made by Parker (Ref. 4), that flux tubes are formed by convective collapse. In an earlier paper (Ref. 4), this problem was studied assuming an adiabatic collapse and an inviscid fluid. These assumptions will now be relaxed and a realistic energy equation will be used which allows for the possibility of radiative heat exchange between the flux tube and the ambient medium. The nonlinear time dependent MHD equations will be solved as an initial value problem. For mathematical tractability, a thin flux tube approximation is used.

2. METHOD

2.1. Initial Equlibrium

Consider a vertical flux tube extending from the photosphere down into the convection zone. Initially, it is assumed that the tube is in hydrostatic equilibrium and that the temperature inside and outside the tube at each depth are the same. An initial stratification using a VAL/SP model atmosphere (taken from Ref. 5) is used. The equilibrium is parametrized by $\beta=8\pi p_o/B_o^2$, where p_o and B_o denote the pressure and magnetic field strength at the initial instant. A representative value of $\beta=7$ is used as this corresponds to an initial equipartition field (~500G at z=0).

2.2. General

The initial equilibrium is perturbed by introducing a small downflow in the tube. To determine the state of the flux tube at later instants, the general MHD equations in the thin flux tube approximation (Ref. 5) are solved using the Flux Corrected Transport method (Ref. 1). The boundaries of the tube are taken at z=-500km and z=2000km (z measured along the tube axis and positive into the Sun), where z=0 corresponds to optical depth unity in the external medium. In the computations, the mass flux at the boundaries is the only parameter that is externally fixed. 'Floating' boundary conditions are used for the other variables.

3. RESULTS

Fig. 1 depicts the variation of B (magnetic field), V (velocity) and T (temperature) at z=50km for a_{oo}= 300km, where a_{oo} is the tube radius at z=0 at the initial instant and for $\nu=10^{12}$ cm^2/s, where ν is the kinematic viscosity assumed to be constant. The onset of instability is characterized by a monotonic increase in B and V and a monotonic decrease in T, which initially is gradual, but later more rapid. After a few hundred seconds the monotonic behaviour stops and oscillations commence. A striking feature of the feature of the results is the existence of overstability ie, the amplitude of the oscillations grows in time. The period of the oscillations changes from 1150s in the first cycle to 1050s in the second cycle. There is a phase difference between B and T of 90° and between V and T of some 180°. The

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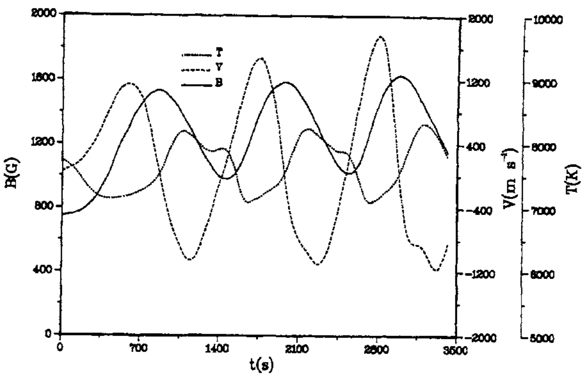

Figure 1. The variation with respect to time of B (solid line), V (dashed line) and T (dotted line) at z=50km.

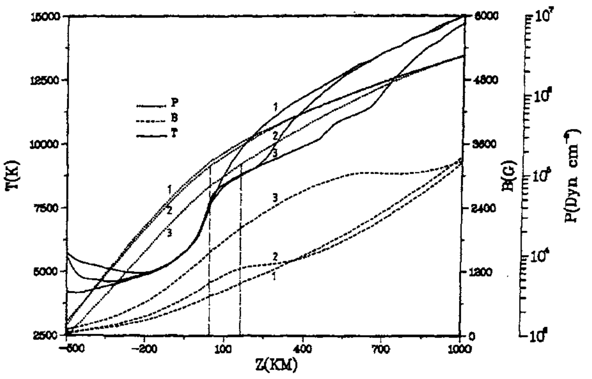

Figure 2. The spatial dependence of T (solid line), B (dashed line) and P (dotted line). Curves 1,2 and 3 correspond to times 0,1500s and 2000s respectively.

time-averaged values of B over an oscillation period increase from 1250G to 1500G, whereas the time-averaged values of T remain close to about 7650K in the first 4000s. On average, V is close to zero. The amplitude of the oscillations increases from 300G to 450G for B, from 550K to 650K for T and from 1.2km/s to 1.8 km/s for V.

Figure 2 shows the spatial variation of T,B and P (pressure) at the initial instant and at two intermediate times, the latter chosen in a way to depict the maximum deviation during an oscillation. Between z=200km and z~0, the curves for T are essentially identical, because radiative exchange is extremely efficient in these layers. For z>0, the tube is cooler on average than its surroundings. The two vertical broken lines are drawn from the P curves 2 and 3 at the place where P=1.3 x 10^5 dyn/cm^2. This may crudely be regarded as the 'observable' level in the tube ie, the level where the continuum optical depth is unity.

3. DISCUSSION AND OBSERVATIONAL IMPLICATIONS

The results demonstrate that intense magnetic fields can be formed by convective collapse. It is further found that the end state of the convective instability is not a steady state, but one exhibiting overstable oscillations with a period around 1000s. Physically, these can be understood as follows: initially, the superadiabatic temperature gradient drives a convective instability which leads to collapse and field intensification. The instability is eventually quenched when the magnetic field becomes strong enough and thereafter oscillations begin. Radiative heat exchange permits the oscillations to draw energy from the surroundings medium and consequently grow in amplitutde.

Consider now some of the observational implications. At the 'observable' level, B varies from 1000G to 2000G, yielding an average value of 1500G, which is in the observed range. Another consequence of the results is that flux tubes should appear hotter than their surroundings owing to the depression of the 'observable' level into the Sun, although in reality they are cooler at the same geometric depth (for z>0). Theory also predicts the existence of an oscillating flow within the tube with an amplitude in the range 1 - 2 km/s. However, such flows are unlikely to yield a net red shift in observations of V profiles owing to time averaging and also because several tubes with random phases are typically involved in an observation. This prediction is compatible with the results of Stenflo and Harvey (Ref. 8). On the other hand, a brightness velocity correlation could be observationally detected and compared with the results which predict an anticorrelation between velocity and temperature. The theoretical consequences of the results for the brightness velocity correlation and on whether they can reproduce asymetries in the V profiles (Ref. 8) are under investigation.

4. REFERENCES

1. Boris, J.P. and Book, D.L. 1976, J. Comp. Phys., 20, 397.

2. Frazier, E.N. 1970, Solar Phys., 14, 89.

3. Giovanelli, R.G. and Slaughter, C. 1978, Solar Phys., 57, 255.

4. Hasan, S.S. 1984, Astrophys. J. (in press).

5. Hasan, S.S. and Schüßler, M. 1984, Astron. and Astrophys. (submitted).

6. Parker, E.N. 1978, Astrophys. J., 221, 368.

7. Spruit, H.C. 1977, Ph.D thesis, University of Utrecht, 26.

8. Stenflo, J.O. and Harvey, J.W., 1984, Solar Phys. (in press).