CONVECTIVE COLLAPSE OF FLUX TUBES

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Abstract. Flux tubes of constant $\beta$ extending vertically through the solar convection zone are unstable to a convective instability if the surface field strength is less than $1270 \text{ G}$. By downward displacement of matter along the tube an unstable tube can transform into a new equilibrium state with lower energy which has a higher field strength. Numerical calculations of these 'collapsed' states are presented. If the collapse starts in a field with a strength corresponding to equipartition with kinetic energy in the convection zone, it yields a surface field strength of about $1650 \text{ G}$. It is proposed that the small scale magnetic field in active regions consists of such tubes. The collapsed state is not in thermal equilibrium. In the deeper layers the heat exchange following the collapse is very slow but the surface layers return rapidly to temperature equilibrium. It is argued that during the gradual thermal evolution of the collapsed state its surface layers may start an overstable oscillation. A brightness-velocity correlation in this oscillation could account for the observed downdraft in the tubes.

1. Introduction

Parker (1978) has suggested that the high field strengths observed in the small scale magnetic field of the Sun are due to a convective process in an originally weaker field. He argued that a downward flow in a flux tube can be maintained by buoyancy forces and that it is cooler than its surroundings (like an intergranular lane). The integrated effect of this temperature reduction over several scale heights is a reduced pressure at the surface, resulting in a high magnetic field.

Since a vertical magnetic field has a stabilising effect on convection, we expect that this process occurs only if the initial field strength is low enough. In Spruit and Zweibel (1979) we determined the critical field strength of the process, i.e. the field strength at the onset of convective instability in a flux tube. This instability has also been studied by Unno and Ando (1979), and Roberts and Webb (1979). We assumed that the initial flux tube was in temperature equilibrium with its surroundings. In this case the critical field strength, $B_c$, for the solar convection zone, was found to be $1270 \text{ G}$ at the solar surface. Since the observed field strengths in active regions are generally above this value, we concluded that the observed tubes are probably stable.

It is of interest to study what happens to an unstable tube. If the instability sets in as a downward flow, the tube cools with respect to its surroundings and its field strength increases. The higher field, however, has a stabilising influence. Hence we guessed (Spruit and Zweibel, 1979) that there is a limit to the downward displacement; i.e. the tube can transform into a new equilibrium state with a lower energy, lower temperature and higher field strength. If on the other hand the instability sets in as an upward flow, the field strength decreases, and the instability becomes stronger. In this case

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we expect normal convection in a dispersed field to be the end result. These processes lead to the following interpretation of the concentrated nature of the solar surface field. If, for whatever reason, the field strength of a patch of magnetic flux drops below 1270 G, the convective instability transforms it into either a dispersed patch of vanishing field strength, or into a stable concentrated path with a strength higher than 1270 G. This process takes place on a hydrodynamic time scale, i.e., comparable to the granule turnover time ($\approx 15$ min). Hence it seems likely that the process will rarely be observed while in progress but that what one observes are its end products. Also it seems unlikely that the downflow associated with the instability gives rise to the observed downdraft in flux tubes. The observed universality of the downdraft requires a more continuously operating mechanism.

The purpose of this paper is to make the above ideas more quantitative. We do this by calculating the possible equilibrium states of flux tubes which are originally in pressure and temperature equilibrium with their surroundings, and by calculating which of those states (if any) have a lower energy.

The interpretation given here of the concentrated nature of the small scale field differs from that by Peckover and Weiss (1978) and Galloway et al. (1977, see also the references therein). Their mechanism is based on the interaction between a flux tube and a surrounding convective cell, and requires the presence of a turbulent viscosity. By contrast, the process described here does not depend on an external flow and is not modified basically by the presence of viscosity.

2. Assumptions

For the equilibrium state serving as the starting point of our calculations we take a flux tube in which $\beta = 8\pi P/B^2$ is a constant, $\beta_0$ (independent of depth). This corresponds closely to assuming temperature equilibrium between the tube and its surroundings. As a (partial) justification of this assumption we note that on a sufficiently long time scale a stable flux tube tends to temperature equilibrium by radiative diffusion.

We assume that the tube is narrow, so that the thin tube approximation (Roberts and Webb, 1978) can be applied (see also Spruit and Zweibel, 1979), and we neglect magnetic diffusion ($\eta = 0$). Finally, we assume that the change from the original to the new equilibrium state takes place adiabatically. The reason for doing this is that time scales for radiative diffusion in the convection zone are much longer than the (hydrodynamic) time scale of the process considered here. The approximation fails near the solar surface, but this probably does not influence the results strongly, because the mass in those layers of the tube is negligible. The approximation also fails if one considers the behavior of the new equilibrium on very long time scales; we discuss this in Section 4.4.

2.1. Equations

We want to calculate possible equilibrium configurations which can be derived, by