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THEORETICAL MODELLING OF THE FINE STRUCTURES IN SUNSPOTS

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Until a decade ago most solar physicists thought of a sunspot as the upper end of a giant flux tube floating vertically. Parker (1979a) provided an alternative scenario in his spaghetti model and showed that many properties of sunspots can be understood better if sunspots are regarded as loose collections of fibril flux tubes. In spite of the many attractive features of this model, it is probably fair to say that we are still unable to give an unequivocal verdict in favor of one of the two models on the basis of current observations. Since we cannot hope to observe the subphotospheric magnetic structures directly, the wisest strategy seems to be to work out systematically those consequences of both models which should be distinguishable from high resolution photospheric observations. One approach to this problem discussed here is to do detailed theoretical modelling of sunspot fine structures within the frameworks of both the rival models, in order to provide a basis for future crucial observations from space. Another approach currently under investigation by Bogdan (1986) is to study the scattering of p-modes both from single flux tubes and from collections of fibrils, and then to compare theoretical results with observations.

The existence of umbral dots and penumbral grains has been known for several decades. However, their individual sizes are smaller than the limit set by atmospheric seeing, and consequently their properties cannot be studied with sufficient reliability from gound-based observations. On the basis of available observations, they seem to be regions of photospheric intensity with upflowing gas motion and magnetic fields much weaker than in the surrounding sunspot surface. References to the relevant observational papers are given in Choudhuri (1986). It is not even clear whether umbral dots and penumbral grains can be regarded as convective cells within the sunspots. Claims have been made both for (Bumba and Suda 1980) and against (Loughhead, Bray and Tappere 1979) this hypothesis by different observers.

On the theoretical side also, a magnetoconvective theory of umbral dots has been considered by Knobloch and Weiss (1984) that can be fitted with the single-flux-tube model of sunspots. They suggested that the differences in the appearances of umbral dots and granular cells are caused by the highly nonlinear nature of the convection problem in the presence of strong magnetic fields. Full calculations to substantiate these ideas have not been carried out yet. On the other hand, Parker (1979a,b) explained umbral dots within the framework of his spaghetti model as regions where field-free gas intrudes through the clustered flux tubes from underneath the surface. Elaborating on these ideas, Choudhuri (1986) investigated how the surrounding magnetic field may try to close on the field-free gas from the top and control the dynamic behavior of the system. Here we merely present the main ideas without any equations. Readers are referred to the original paper for the details of calculations.

It can be shown that a pocket of field-free gas surrounded by a vertical magnetic field in the presence of gravity takes up the shape of a tapering column ending at a vertex at the top, as shown in Figure 1a. Choudhuri (1986) first studied the static equilibrium of such a system. Regions away from the apex can be treated by slender flux tube approximation. However, special care is needed to treat the region around the apex. An exact solution for that region in two dimensions and an approximate solution in three dimensions were presented. It was found that, just below the apex, the radius of the tapering column opens up with a 3/2 power dependence on the depth below the apex. When the analytical solutions for the two different regions are

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combined together, it agrees quite well with numerical calculations. The vertical position of the apex depends on the internal pressure of the field-free gas. If the internal pressure is increased, the whole tapering column rises.

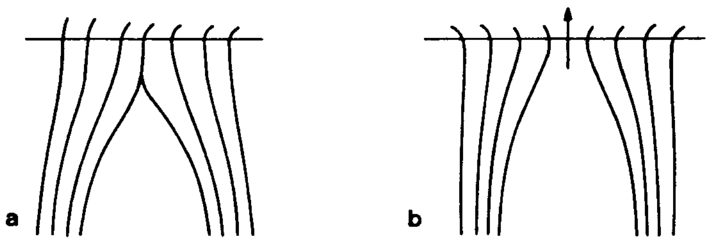

FIG. 1

We expect some convection to take place in the trapped field-free gas, whereas the magnetic field around it makes those regions stable against convection. Hence heat can be transported convectively upward into the trapped field-free gas, but no further convective transport is possible to allow that heat to reach the surface. Since radiative diffusion is rather inefficient once we go some distance below the photosphere, we expect to have a situation where the temperature and pressure of the trapped gas keep growing, causing the whole tapering column to rise. Plugging in typical values of different quantities shows that the velocity of rise is small compared to sound speed. Hence the system can be thought to evolve through a succession of quasi-static states in mechanical equilibrium.

Eventually the apex of the tapering column reaches the photospheric surface where the bulging of the magnetic field makes the field no longer able to close on the field-free gas and trap it underneath. A flow path is thus established as shown in Figure 1b. An analysis of the steady flow problem shows that the velocity of the upcoming gas at the mouth of the flow path should be of the order of Alfvén speed in the surrounding magnetic field. After a sufficient amount of field-free gas has escaped, thereby reducing its internal pressure, it may no longer be possible to maintain a flow path and the field may again close up, stopping any further escape of the field-free gas. Thus the field geometry effectively acts as a magnetic valve. When there is sufficient pressure under it, the magnetic valve opens and allows the trapped gas to come out. But after enough gas has escaped to reduce the pressure sufficiently, the magnetic valve closes and chokes off the flow. An umbral dot can simply be regarded as an open magnetic valve through which field-free gas from below is coming out. Since magnetic field in the penumbra is inclined to the vertical, we expect the flow path also to be inclined, and a simple projection effect can explain the elongated shape of the penumbral grains.

It seems that this model is consistent with most of the current observations. However, the ultimate fate of the model will certainly depend on whether it will be able to explain the future high-resolution observations from space.

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