THE MAGNETIC FIELD CONFIGURATION IN SOLAR AND STELLAR CHROMOSPHERES

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ABSTRACT

Calculations are presented for the inhomogeneous magnetic field structure above a stellar photosphere which has magnetic flux tubes located at the downdraughts of its supergranulation pattern. Regions can be delineated where the ambient magnetic energy density is large or small compared with the thermal energy density derived from a model atmosphere. This enables the relative importance of magnetic versus non-magnetic heating mechanisms to be assessed. For the quiet Sun, over half the chromospheric emission must be supplied non-magnetically, whilst the network and active regions require a magnetic supply. For other late-type stars, a simple working rule suggests that when the magnetic field is strong enough to be directly observable, the chromosphere will be magnetically dominated.

1. INTRODUCTION

The quiet Sun's photospheric magnetic field is concentrated into thin tubes which are most commonly located in the regions of convective downdraught at the boundaries between supergranulation cells. In the chromosphere above, the field fans out and flux from the different tubes merges to give a field which is more uniform by the time the corona is reached. In this paper we give a three-dimensional calculation of this fanning-out structure based on the hypothesis that the field in the atmosphere is current-free and use it to decide where and when in the chromosphere magnetic versus non-magnetic heating mechanisms are important. Two-dimensional calculations have already been given by Kopp and Kuperus (1968) and Gabriel (1976); less detailed 3-D models are shown in the paper on coronal plumes of Newkirk and Altschuler (1968), and models for various isolated tubes are given in Simon et al. (1982). The work here considers a horizontally periodic atmosphere with tubes stationed at strategic points in a hexagonal supergranulation pattern.

The calculated models are static with simple field configurations, and are thus best suited for treating quiet regions. For the Sun, Avrett

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(1981) has worked out in this case the run of chromospheric radiative losses as a function of height, basing his calculations on the model atmospheres of Vernazza et al. (1981). The losses peak at a height of around 850 km, and fall off exponentially above 1000 km. In a steady state, these losses must be supplied by some form of mechanical heating; Ulmschneider (1981) advocates non-linear acoustic waves, and the divergence of the flux of these waves appears to be able to reproduce Avrett's loss curves. Ulmschneider and Stein (1982) have also argued that in the network an essentially magnetic mechanism must operate, and indeed the large excess emission there and in active regions indicates that such a mechanism is far more efficient when given a chance. It is thus important to work out where in the chromosphere the field dominates, and where by contrast it is so weak that wave motions are essentially acoustic or gravitational in nature. We shall do this numerically for the Sun, and then provide an approximate working rule for use with other stars. A full description of this work will be available in Anzer and Galloway (1982).

2. OUTLINE OF THE MODEL

The bottom boundary of the model is taken to be a plane consisting of a periodic pattern of hexagons representing supergranulation cells. The magnetic field at this boundary is concentrated into individual tubes whose centres are located at strategic points on the lines separating the hexagons, i.e. in the convective downdraughts. Each tube is small compared with the supergranule half-width L, and the vertical component of field B_z at its bottom boundary is uniform out to some radius R, and thereafter zero. All hexagons are identical. Various different configurations have been run; the one illustrated in this paper has tubes at each vertex (figure 1).

The field above the boundary z=0 is calculated on the assumption that it is current-free. The resulting potential problem can then be solved by Fourier series; for a $\underline{B}$-field which is even in the horizontal directions x and y, the solution can be written

$$B_z = \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} B_{mn} \cos(m\alpha x)\cos(n\beta y)\, e^{-\gamma_{mn} z}$$

together with corresponding sine/cosine expressions for B_x and B_y, where $\alpha = \pi/\sqrt{3}\,L$, $\beta = \pi/L$, $\gamma_{mn} = (m^2\alpha^2+n^2\beta^2)^{1/2}$, and the B_{mn}'s are calculated from the distribution of B_z at z=0. When the tube is centred at (X,Y), and has a radius R and a uniform B_z of 1 at z=0, the Fourier coefficients can be calculated analytically; the resulting formulae for the B_{mn}'s are given in terms of Bessel functions in AG 1982. Several such tubes are then superposed, and the field at any desired (x,y,z) is found by summing the Fourier series on a computer. In two dimensions a full analytic solution is possible (see AG 1982).

To describe the importance of the magnetic field in various regions of the chromosphere, we will consider the 'equipartition surface' (EPS),

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defined as the level z(x,y) where magnetic and gas pressures are equal; thus z solves

$$B^2(z)/8\pi = p(z)$$

and is easily found numerically for any (x,y) once the $\underline{B}$-distribution is known and a model atmosphere (normally VAL (1981) model C) is prescribed. Above this surface the ambient magnetic energy density dominates over the thermal energy density, while below it the opposite is true. In consequence energy transport is likely to be magnetically controlled in the regions above, but to proceed essentially non-magnetically in those below.

3. RESULTS

For the quiet Sun, we have considered a variety of cases with average field strengths B_0 up to 10 G, assorted tube layouts, and a supergranule length scale 2L of 20 000 or 30 000 km. For reasons which will become clear in a minute, only the value of B_0 is really important in determining the height of the EPS away from the immediate neighbourhood of the flux concentrations. Thus here we show only one example, in figure 1, where the EPS is displayed for one hexagon of a planform with L = 15 000 km and a B_0 of 10 G concentrated into tubes of strength 1500 G at each vertex, so that the tubes each have radius 909 km.

Various other calculations were run, and some can be found in AG 1982. In all appropriate cases, away from the immediate surroundings of the flux tubes the EPS lies several scale heights above those regions where, according to Avrett (1981), the dominant chromospheric losses occur. This means there are large areas of quiet Sun requiring a non-magnetic heating mechanism (and, correspondingly, smaller areas in the network that require a magnetic one.) To quantify this, we note that for figure 1, some 76% of the EPS lies above 1000 km (61% above 1300 km), whereas Avrett's (1981) radiative losses peak at a height of 800 km, and decrease approximately exponentially above 1000 km. Though the non-magnetic regions radiate less than the network, their greater area means they actually contribute slightly more than half of the quiet Sun's total chromospheric emission. Taking a B_0 which is less than the rather high value 10 G increases the height of the EPS even further. Moreover, test cases where 'hidden flux' (Stenflo, 1982) is included in the form of small bipolar regions located away from the sides and vertices of the hexagon, show little difference. One must include substantially more net flux before the EPS comes down as low as the radiative losses. For instance, using a B_0 of 110 G, we have been able to obtain results similar to those of Giovanelli and Jones (1982), who found observationally a value of around 500 km for what they call the 'canopy', a concept corresponding loosely to our EPS. Their study was for active regions, which, not surprisingly, are primarily magnetically heated.

For other stars, some less elaborate recipe is helpful. For unipolar regions it turns out that the EPS lies roughly half above and half

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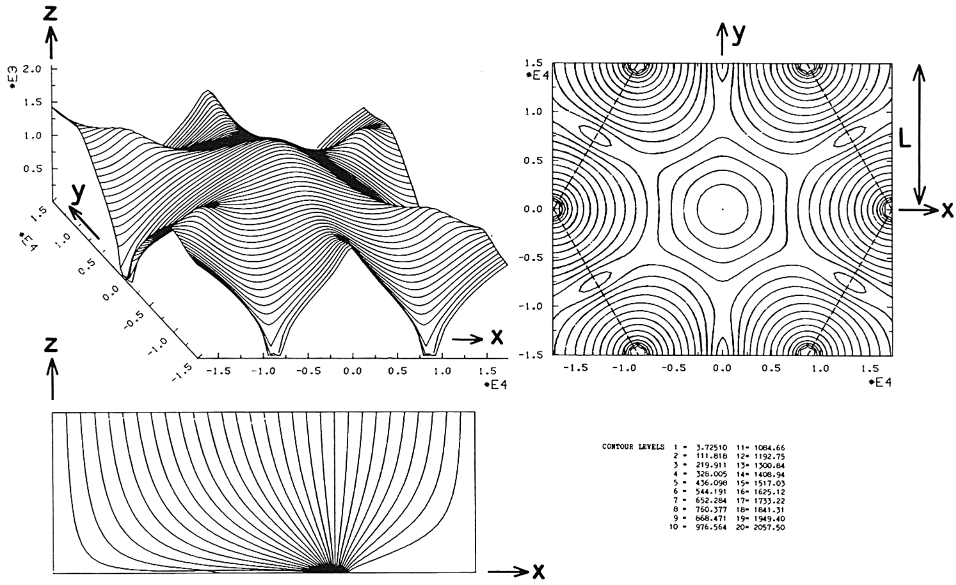

Fig. 1: Perspective plot and contours of the EPS, for the run in the text. Also shown are the field lines in the vertical plane y=0, continued to $x=L\sqrt{3}$. Distances in km.

below that level where $B_0^2/8\pi=p$. For the analogous 2-D problem the result is exact, as is proved analytically in AG 1982. Observational information is rather scanty to apply this result to other stars: either B_0 or $p(z)$ can sometimes be inferred, but both together are known only for the Sun. In AG 1982 we used fields in ξ Boo A and 70 Oph A measured by Robinson et al. (1980), and the model of Arcturus due to Ayres and Linsky (1975), to suggest that late-type stars with directly observable fields should have magnetic chromospheres.

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DISCUSSION

SPRUIT: The surface you are talking about is not the same as the interface between the field and the field free atmosphere, since you left out the corresponding currents in your calculations. Could this be the cause of the discrepancy?

GALLOWAY: We estimated that Giovanelli's procedure corresponds loosely to finding the surface $B^2/8\pi = 0.5p$ in our model. This is indeed lower than the EPS, but not by enough to explain the apparent discrepancy between these results and the latest measurements of Giovanelli and Jones on the poster downstairs.

CAMPOS: I think that the concept of the equipartition surface (EPS) is a magnificent one; it is defined by equality of gas and magnetic pressure. It corresponds to the sound speed being equal to the Alfvén speed (apart from a factor of $2/\gamma$, which is close to unity). Thus this surface can be interpreted in terms of waves: a magnetosonic wave behaves below it as a hydrodynamic wave dominated by compressibility, and above it as a hydromagnetic wave dominated by the magnetic field. The EPS is a critical layer separating these two different regimes, and could be a level of wave absorption.

Now I have a question: The surface (EPS) reaches up to 1300 km for a mean magnetic field $B_0 = 10$ G. What is the influence of different values of B_0 on the height of the EPS? Can it reach into the transition region? Or can you say that, for realistic values of B_0, it does not reach the transition region?

GALLOWAY: If the field is unipolar, parts of the EPS begin to penetrate the transition region when the field average B_0 gets down to about 2 G. When the polarity is mixed there are smaller intrusions for higher B_0, in those regions where the field cancels. I do not know if such regions have any particular significance on the Sun.

BASRI: I have become somewhat confused about what can be learned about heating rates from your results. If the chromosphere is concentrated within fluxtubes, then the tubes would still be confined at 850 km (where the heating rate has a maximum). If indeed most of the heating occurs outside these tubes, why has this conference concentrated so much on fluxtubes?

GALLOWAY: According to Avrett (1981), the non-network parts of the chromosphere have appreciable radiative losses and thus require a heating mechanism. Although of course the losses are greater in the network regions, their smaller area means that they contribute only about half the chromospheric total emission. We have shown here that the *non*-network regions are essentially non-magnetic, so you have to supply their losses some other way, by sound or gravity waves. I appreciate that this goes against the current fashion for magnetic fluxtubes, but that is just what comes out of the calculation. I can only say in apology that one must still heat the network with fluxtubes, and that they will be the dominant mechanism for stars more active than the Sun, which seems to be a borderline case in this respect.

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NORDLUND: The crucial assumption in your calculations is that the chromosphere is current free; thus the gas pressure is assumed to be only a function of height (uniform horizontally), and you plot the level where the magnetic pressure is equal to the gas pressure. You therefore get results similar to those of Spruit, who assumes a negligible gas pressure inside the fluxtubes and derives heights for equilibrium between the tube magnetic pressure and the external gas pressure.

If we consider the real situation, there are significant sources of gas pressure (above hydrostatic) inside the magnetic fluxtubes; spicules shoot up, are heated above Hα temperatures, and "rain down" through transition-zone temperatures. With enhanced internal gas pressure, equilibrium can only be achieved with lower canopy heights, such that the external pressure can balance the *sum* of the magnetic pressure and the internal gas pressure. Thus the *determining factor* for the height is the strength of the source of extra gas pressure inside the tubes! Do you agree?

GALLOWAY: It depends on how cynical you want to be about the model atmospheres. One gets the impression reading VAL that the things you are suggesting do not occur with sufficient vigour to affect the derivations, and without any more information one just has to assume that the job is being done properly. However, it is certainly true that there are spicules in the network, and that these are *very* far from hydrostatic equilibrium. If there are indeed corresponding supersonic motions filling the regions above supergranule centres, I agree that the picture given here will have to be altered.

GIOVANELLI: Mathematicians can get exact answers to problems where the boundary conditions are prescribed, but these do not necessarily tell us anything about the real Sun. It is the latter that we should be concerned about. Indeed, the Sun is extremely complicated, with all sorts of chromospheric structures — including the spicules and the fibrils, both of which originate in the magnetic network. They are magnetic structures.

Dr. Jones and I have been concerned with trying to find out how the magnetic field expands with height in the Sun, not in a model. It is necessary to study in detail how the magnetograph responds to canopy-type fields, where the field is not uniform through the region of line formation. It is necessary to use non-LTE excitation and make proper allowance for magnetic pressure. We have explored as full a range of atmospheric models as we could find, e.g. models A-F of Vernazza, Avrett, and Loeser. The conclusions we derive (1982, *Solar Phys.* **79**, p. 247) seem to give canopy heights with uncertainties of the order of ± 50, perhaps ± 75 km, but the field strengths are not well determined.

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