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LETTERS

The heating of the solar transition region *

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Abstract The temperature curve in the solar chromosphere has puzzled astronomers for a long time. Referring to the structure of supergranular cells, we propose an inductive heating model. It mainly includes the following three steps. (1) A small-scale dynamo exists in the supergranulation and produces alternating small-scale magnetic fluxes; (2) The supergranular flow distributes these small-scale fluxes according to a regular pattern; (3) A skin effect occurs in the alternating and regularly-distributed magnetic fields. The induced current is concentrated near the transition region and heats it by resistive dissipation.

Key words: Sun: transition region — Sun: granulation

1 INTRODUCTION

The problem of why the temperature of the Sun's corona is a few hundred times the average temperature of its surface is still unresolved in solar physics. Since its discovery, many heating models have been proposed. Nowadays there exist two prevailing theories. One comes from Parker (1983, 1988). It suggests that thousands of nanoflares which occur in the tangled magnetic fields can provide enough energy. Priest et al. (2002) developed this idea and constructed a detailed flux-tube tectonics model. The other was first given by Uchida & Kaburaki (1974). It states that the heat source is Alfvén waves which are transferred along the magnetic field lines. Using images taken by the HINODE satellite, De Pontieu et al. (2007) found tracks of Alfvén waves permeating the solar chromosphere. Antolin et al. (2008) thought that the former one is more adequate for active region loops, and the latter one applies for quiet sun loops. Although the way of heating is different, both ideas emphasize that the driving role is played by the continuous motions of the photospheric foot points of the flux tubes. Goodman (1995) built a global resistive MHD model to explain the heating problem of the quiet solar middle chromosphere. He thought that heat is generated by the resistive dissipation of large-scale electric currents. By considering the principle of the inductive heating technique, which has been widely used for heating the surfaces of metallic machine parts, here we propose a similar idea. In the thin solar transition region, the temperature increases rapidly and the density drops dramatically. However in the much thicker chromosphere, the temperature increases very slowly. Such a phenomenon shows that chromospheric heating also favors surfaces, just like the skin effect taking place in those metallic machine parts.

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2 METHOD

The supergranular velocity field was first reported by Hart (1954, 1956) and then confirmed by Leighton et al. (1962). Its cells are defined by horizontal outflows from regions of up-welling at their center to sinks at their boundaries, with typical diameters of 30000 km, rms velocities of 500 m s^{-1} and lifetimes of 10^5 s. There exists a strong spatial correspondence of supergranular cell boundaries with the magnetic network and the chromospheric emission network (Simon & Leighton 1964). About 5000 such cells cover the Sun at any time.

Gabriel (1976) gave a magnetic model of the solar transition region and assumed that the magnetic flux is totally excluded from the supergranular cell so that there is an interface between plasma having a velocity field but no magnetic field, and plasma having a magnetic field but no velocity field. As shown in Figure 1, we draw the velocity field of a supergranular cell with arrow lines. The center upflow possibly brings some inner small-scale magnetic flux up to the solar surface, and then the horizontal flow defines the path to return to the photosphere. As a consequence, we get a magnetic field that is completely parallel (or antiparallel) to the velocity field.

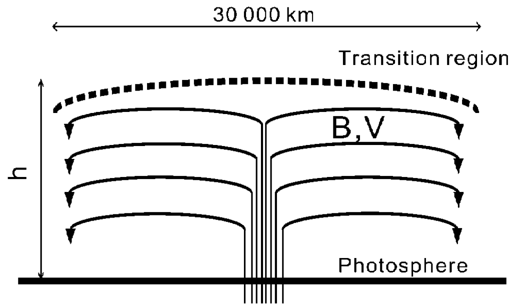

Fig. 1 A supergranular cell. Arrow lines indicate the magnetic field (regardless of the polarity) and the velocity field.

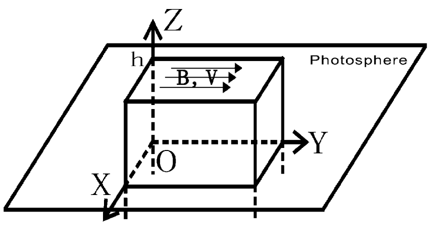

Fig. 2 For simplifying the treatment, we extend the right half of Fig. 1 into an infinite plane. The magnetic field only has gradients in the $\boldsymbol{e}_z$ direction and only has values in the $\boldsymbol{e}_y$ direction.

In order to simplify the treatment, we assume that the magnetic field ($\boldsymbol{B}$) has gradients only in the height direction and only has values in the velocity direction. Moreover, it is sustainable and varies continuously in time as a pure sine wave. Figure 2 gives the Cartesian coordinate where the right half of Figure 1 is extended into an infinite plane. Thereupon, we have the following equations:

$$\boldsymbol{B} = B(z)e^{-i\omega t}\boldsymbol{e}_y, \quad (1)$$

$$\nabla^2 \boldsymbol{B} = \mu\sigma \frac{\partial \boldsymbol{B}}{\partial t}, \quad (2)$$

$$\boldsymbol{J} = \frac{1}{\mu}\nabla \times \boldsymbol{B}, \quad (3)$$

where μ is the magnetic permeability, and σ is the electrical conductivity. Its solution is $\boldsymbol{B} = A_1 e^{\sqrt{\mu\sigma\omega/2}z} \cdot e^{i(-\sqrt{\mu\sigma\omega/2}z-\omega t)}\boldsymbol{e}_y + A_2 e^{-\sqrt{\mu\sigma\omega/2}z} \cdot e^{i(\sqrt{\mu\sigma\omega/2}z-\omega t)}\boldsymbol{e}_y$. For the chromosphere, using the Spitzer formula $\sigma = \frac{\gamma_e T^{3/2}}{38Z\ln\Lambda}$, we obtain $\sigma = 712\,\mathrm{S\,m^{-1}}$, here $\gamma_e = 0.582$, $T = 6000$ K, $Z = 1$, and $\ln\Lambda = 10$. The thickness (h) of the chromosphere is about 2000 km making $\sqrt{\mu\sigma\omega/2}h$ large enough to form a skin effect, namely, the magnetic field is mainly distributed in the upper and lower surfaces of the horizontal flow. If the magnetic field strength equals B_0, the corresponding current density strength $J = \sqrt{\sigma\omega/2\mu}B_0$. This can result in an inductive heating power,

$$P = \frac{J^2}{\sigma} = \frac{{B_0}^2\omega}{2\mu}. \tag{4}$$

3 DISCUSSION

Are there observational signatures of the magnetic field located in a supergranular cell? The answer is affirmative. They are the intranetwork flux (IF). Wang et al. (1995) suggested that the small-scale dynamos (e.g., Petrovay & Szakaly 1993; Durney et al. 1993) near the base of the supergranulation could be a possible source of IF. The converging motion of the supergranulation gathers some IF towards its center, and brings them up to the solar surface. Due to either their small diameter, or weak field strength, the IF does not experience buoyancy or tension forces, but mainly follows the dynamical drag force of the supergranular motion. Equation (2) does not mean that the magnetic field changes are due to the diffusion. In fact, it is modulated by the dynamos that produce them. The diffusion is only an evoked response. Therefore we think that the real energy source is the small-scale dynamos.

Another important aspect is to determine the thickness of the layer in which the horizontal flow takes place. By considering mass balance, Küveler (1983) estimated it to be 150 km without considering the rapid decrease of density with height. According to Gabriel (1976)'s idea that the rate of flux expansion hinges on the vertical extent of a supergranular cell, we believe the upper surface of the horizontal flow to be near the transition region. The chromospheric emission network also fades away while going through the transition region. On the other hand, for the higher density region below the photosphere, the depth of the bottom surface of the horizontal flow must be less than that of Küveler's estimation. We set $B_0 = 5.9\,\mathrm{G}$ in the upper and lower surfaces. This average field strength is measured by Wang et al. (1995) for more than 2500 individual IF elements. The parameter $\omega = 2\pi/T$, where $T = 3.4$ min indicates the average lifetime of IF in the quiet sun, was obtained by Shi et al. (1990). From Equation (4), we obtain a heating power of $P = 4.27 \times 10^{-3}$ W m^{-3}, which is close to the radiative loss at the top and bottom of the chromosphere calculated by Avrett (1981). A much longer average lifetime, 46 min, of IF was found by Lin (1997) in a solar coronal hole on 1993 June 23. This may be the reason why the coronal hole has a lower temperature.

At present, the heating of the chromosphere and of the transition region are often studied separately. Except for those models designed wholly for the transition region (e.g., Pneuman & Kopp 1978; Rabin & Moore 1984; Woodset al. 1990), most of the others do not include a dissipation mechanism which mainly exists in such a thin layer (e.g., Heyvaerts & Priest 1983; Berger 1991; Vekstein et al. 1991; Choudhuri et al. 1993). With the introduction of the skin effect, our model can provide a possible explanation, if given a reasonable dynamo to sustain the horizontal magnetic fields. Although the electrical conductivity has no relation with the inductive heating power (see Eq. (4)), it is very important because both the current density strength and the depth of skin effect depend on it. Goodman (1995) assumed the conductivity stays constant in the chromosphere and obtained a value of $1.24 \times 10^{-2}\,\mathrm{S\,m}^{-1}$ (or the resistivity equals 9×10^{-9} s in CGS units) in his model. This low electrical conductivity can also form an obvious skin effect and induce a current density near $7\,\mathrm{mA\,m}^{-2}$. Here the depth of the skin effect (of $1/e$ amplitude) can be defined as $d = 1/\sqrt{\mu\sigma\omega/2} = 65\,\mathrm{km}$, which is comparable to the thickness of the transition region ($\sim 100\,\mathrm{km}$).

4 SUMMARY

Referring to the supergranular velocity structure, we propose an idea to explain the heating of the solar transition region. It mainly includes three steps. (1) A small-scale dynamo exists in the supergranulation and produces the alternating IF; (2) The supergranular flow distributes these IF tubes according to a regular pattern, as shown in Figure 1; (3) Due to the skin effect, the induced current is concentrated in the transition region and heats it by resistive dissipation. Rabin & Moore (1984) proposed a model based on ohmic heating by filamentary electric currents that flow along the magnetic field. The related current filaments are of fine scale, with a narrow dimension in the range of 1 cm to 1 km. Roumeliotis (1991) gave a one-dimensional model to study solar atmospheric structure along a Joule-heated field line embedded in a sheared magnetic boundary layer. He found that the atmosphere along the field line evolves towards a hot equilibrium state (10^6 K> $T_{\max} \geq 8 \times 10^4$ K) when the electric current density exceeds the critical value. Regretfully, both of them do not give arguements regarding where the necessary conditions come from. The advantages of our model are that it is based on the features of solar supergranulation, it naturally connects the transition region to the chromosphere and the plasma flows under the photosphere. Here the details of our analysis are oversimplified. Several questions remain to be addressed in future studies. For example, a reasonable small-scale dynamo model is needed. Here we believe that the HINODE satellite can help us find the origins of IF as well as discover some relations between the characters of IF (e.g., lifetime, magnetic field strength) and their surrounding temperature.

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