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A STEADY FLOW MODEL OF A MAGNETIC FLUX TUBE CONSTRAINED TO OBSERVED DIFFERENTIAL EMISSION MEASURE

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ABSTRACT

We have investigated one dimensional steady flow model of a typical magnetic flux tube in the solar transition region constrained to observed Differential Emission Measure (DEM) for the average quiet-Sun deduced by Raymond & Doyle (1981) with a flux tube geometry conforming to Doppler shifts of UV lines measured by Chae, Yun & Poland (1998). Because local heating and filling factor in the transition region are not well known, we considered two extreme cases, one characterized by the filling factor=1 ("filled-up model") and the other set by local heating=0 ("not-heated model"). We examined how much the heating is required for the flux tube by recomputing a model through adjustment of the filling factor in such a way that "not-heated model" accounts for the observed DEM.

Key words: Sun: transition region, Sun: flux tubes

I. INTRODUCTION

The solar transition region is a thin layer between the chromosphere of 10^4 K and the corona of 10^6 K. Its thickness is only $1\sim2\times10^3$ km comparable with that of the chromosphere, while its temperature variation is of the order of 2. One of the most important findings from recent EUV and UV observations is that the transition region displays dominant downflow motion (e.g., Athay & Dere 1991; Chae, Yun & Poland 1998). Recently, Chae, Yun & Poland (1997) elaborated the energetics and structure of the transition region by constructing theoretical models of a thin rigid magnetic flux tube with a steady material flow embedded vertically in the solar atmosphere with taking into consideration of the effects of material flow, conduction, non-LTE radiative cooling in H and He and partial ionization. They confirmed the previous work (e.g., Athay 1981, 1982, 1990; Boris & Mariska 1982; Mariska 1988, 1992; McClymont 1989) and provided the explanation of the dominance of the downflow by demonstrating why downflowing transition region material is much more visible than upflowing material.

II. STATEMENT OF THE PROBLEM

Despite Chae, Yun & Poland (1997)'s successful demonstration for the dominance of the observed downflow, their model cannot match the Differential Emission Measure (DEM) of Raymond & Doyle (1981) which was derived empirically with the use of the solar EUV composite spectra published by Vernazza & Reeves (1978). DEM is defined as

$$D(T) = \int_{\log(T'(z)/T)=-0.05}^{\log(T'(z)/T)=0.05} N_e^2 dz \qquad (1)$$

Here, T is the temperature as a function of height, z, N_e the electron number density, and D the DEM as a function of T, the temperature. As seen from the definition, DEM depends only on the temperature structure and represents a measure of spatial extent of the transition region.

This DEM plays a crucial role in checking the validity of various models of thermal structures. For examples, the steady flow models generated by Pneuman & Kopp (1978), Athay (1981, 1982), Wallenhorst (1982), Fiedler & Cally (1990) could not account for Raymond & Doyle (1981)'s DEM at the lower temperatures less then 10^5 K. Most of the models presented by Athay (1987, 1990), Boris & Mariska (1982), McClymont & Craig (1986, 1987), Mariska (1988, 1992) and McClymont (1989) could not confirm the validity of the upper transition region where the flux tubes expand outward.

One of the main reasons that previous models do not account well for the observed DEM seems to lie in the fact that they assumed that the cross section of a flux tube does not vary with height. In addition, they have not taken into consideration the effect of the filling factor of magnetic tubes. The filling factor is the ratio of the area of flux tubes over the entire solar surface area.

Recently, SUMER (Solar Ultraviolet Measurement of Emitted Radiation) on board SOHO (Solar and Heliospheric Observatory) has provided a great deal of high quality data of solar UV spectra. Chae, Yun, & Poland (1998) made use of the SUMER's high resolution UV line spectra to derive a reliable set of Doppler shifts covering temperatures ranging from 10^4 to 10^6 K. In addition they estimated the cross section variation of a typical flux tube with temperature, assuming that pressure and mass flux are constant along a flux tube with varying cross section.

It is now widely believed that the coronal heating is of magnetic origin which is excited by interactions between the magnetic field and mass motion in the photosphere. Various physical processes have been considered as possible mechanisms for heating including MHD waves (e.g., Ionson, 1982; Hollweg 1984; Ofman, Davila & Steinolfson, 1995), nano-flares (e.g., Parker, 1983a, 1983b, 1988), and MHD turbulence (Heyvaerts & Priest 1992, Inverarity & Priest, 1995a, 1995b). Thanks to the SUMER's high resolution UV line spectra, Chae, Schuhle & Lemaire (1998) were able to infer the turbulent heating rates from their much improved measurements of velocity fluctuations in the transition region and corona, and demonstrated that the inferred turbulent heating rates account for the radiative heating loss throughout the transition region and corona. However, the nature of the observed nonthermal motions is not yet clearly understood, so that overall elaborate local heating rates are not well established. Accordingly, even a rough estimate of nonthermal heating rates is extremely important since it guides a way to clarify the dominant heating mechanism as well as the physical nature of nonthermal motions.

In the present study we made an attempt to construct a set of simple steady flow models by forcing them to comply with Raymond & Doyle (1981)'s DEM for the average quiet-Sun and the Doppler shifts provided by Chae, Yun, & Poland (1998), and yet by varying the filling factor.

III. THEORETICAL FORMULATION

We consider a thin flux tube embedded vertically in the upper solar atmosphere whose cross section varies with height. We assume that the magnetic field in the tube dominates to the extent that the gas motions do not perturb the magnetic structure so that the flow can be described in one dimension along the flux tube. The temperature and density at each point along the tube are treated as the average horizontal value as described in Kuin & Poland (1991). Conductive energy transport is assumed to be directed only along the tube axis, and the flux tube is conductively insulated from the surrounding medium.

Under these assumptions, the steady flow equations of one dimensional hydrodynamic problem are written as

$$\frac{d}{dz}[\rho v A] = 0 \tag{2}$$

$$\frac{d}{dz}[\rho v^2 A] + A\frac{dp}{dz} = -\rho g A \tag{3}$$

$$\frac{d}{dz}[F_{conv} + F_{cond}] = (H-L)A \tag{4}$$

Here, z is the height, ρ the density, v the velocity, A the cross-sectional area of the flux tube, p the pressure, g the gravitational acceleration of the Sun. Chae, Yun, & Poland (1998) showed that, from their analysis of Doppler shift measurements, A could be fit well with the model of Rabin (1991). Following Chae, Yun, & Poland (1998), we set A as

$$A(T) = \frac{1}{\Gamma}\left[1 + (\Gamma^2 - 1)\left(\frac{T}{T_h}\right)^{\nu}\right]^{1/2} \tag{5}$$

F_{conv}, F_{cond}, and L are the convective energy flux, the conductive energy flux and radiative cooling rate defined respectively, as

$$F_{conv} = \left(\frac{1}{2}\rho v^2 + \frac{5}{2}p + I + pgz\right)v \tag{6}$$

$$F_{conv} = -\kappa\frac{dT}{dz} \tag{7}$$

$$L = N_e N_H \Phi \tag{8}$$

I is the ionization potential energy defined as

$$I = N_H(x_{H+}\chi_{H+} + Bx_{He++}Bx_{He++} + \chi_{He++}) \tag{9}$$

where N_H is the number density of hydrogen, x the ionization ratio, χ the individual ionization energy, and B the helium ratio respect to hydrogen. In the present study B is taken as 0.05 to maintain the consistency with the result of Kuin & Poland (1991). κ is the thermal conductivity of McClymont & Canfield (1983) where partial ionization is taken into account. N_e is the number density of electron, and Φ is the radiative cooling function from Kuin & Poland (1991).

IV. RESULTS AND DISCUSSION

In our formulation, there are two crucial unknowns, the heating rate H and the filling factor γ, both of which have to be provided from observations. If one of them were known, one could determine the other one from

Table 1. Lower boundary conditions and the resulting flux tube shpe pameters

Model	p (dyne/cm^2)	v (km/s)	F_{cond}(erg/cm^2/s)	ν	Γ	T_h(K)
filled-up	0.322	−1.14	-2.20×10^2	3.5	30	9.8×10^5
not-heated	0.322	−1.11	-1.44×10^2	3.8	33	8.9×10^5

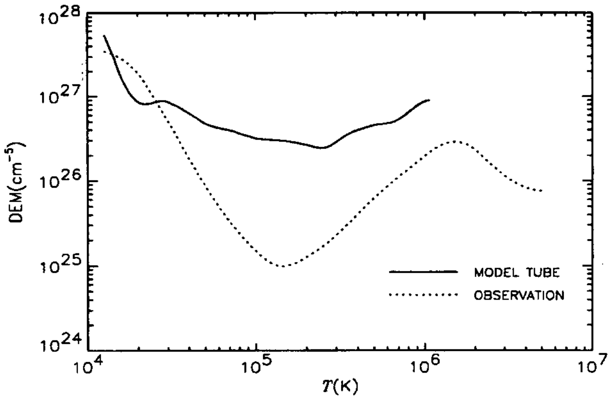

Fig. 1. Computed DEM of two extreme models. The computed DEM of "filled-up model" (dotted line) is adjusted to observations. The solid line refers to the computed DEM of "not-heated model".

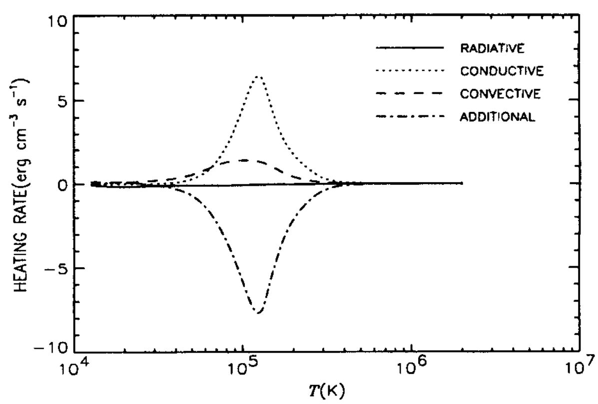

Fig. 2. Energy balance of "filled-up model". Extracted heat (dot-dashed line) is mainly balanced by conductive heating from the corona (dotted line).

the model. But unfortunately, we have little information about both of them. Accordingly, we considered two models with two extreme conditions, one characterized by the filling factor, $\gamma=1$ ("filled-up model") and the other by local heating rate, $H=0$ ("not-heated model"). Table 1 shows physical parameters which characterize these two models. The parameters of the flux tubes are not so different from the result of Chae, Yun, & Poland (1998) where ν, Γ and T_h are 3.6, 30 and 10^6 K, respectively.

In the transition region, the temperature increases so rapidly over a small range of height that we defined an independent variable r to smooth the change of the other variables, including z and T. Actual numerical integration was done with respect to r, using 4th order

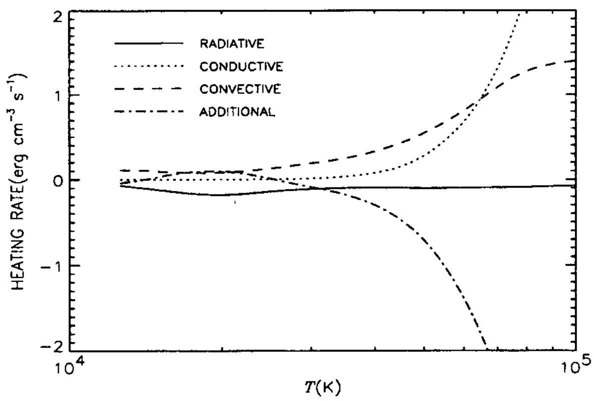

Fig. 3. An expanded view of Fig. 2 in temperature regime around 2×10^4 K.

Runge-Kutta method.

DEM data is available from the temperature log T= 4.1, so we took it as the lower boundary. The height of the lower boundary was set to 2000 km arbitrarily. From this point, we integrated the equations upwards with a set of given initial p and v values. Then these initial values and the flux tube geometry have been adjusted by repeating the integration until $N_e=1.8\times10^{10}$ cm^{-3} at T=6.0×10^4 K (Mariska, 1992) and the observed Doppler shift v.s. temperature relation provided by Chae, Yun & Poland (1998) are obtained.

The resulting computed DEM of these two models are shown in Figure 1. In the figure, the computed DEM of "filled-up model" ($\gamma=1$) has been adjusted to observations and it is denoted by a dotted line. The solid line refers to the computed DEM of "not-heated model". It is noted that the DEM of "not-heated model" exceeds the observed DEM except for the lower temperature regime confined to around 2×10^4 K. In this region the computed DEM becomes less than the observed DEM because greater temperature gradient of "not-heated model" complements the energy loss due to radiative cooling, while this loss is complemented by the external heating in "filled-up model". Figure 2 shows the heating rates of "filled-up model" and Figure 3 is its detailed view confined to below 1×10^5 K . As seen from Figure 2, in order for "filled-up model" to account for the observed DEM, quite a large amount of the additional heat has to be expelled from the flux tube everywhere except for a narrow lower transition region around 2×10^4 K. And the extracted energy of "filled-up model" is mainly supplied by the conductive heating from the corona. However, the heat expulsion is not so feasible

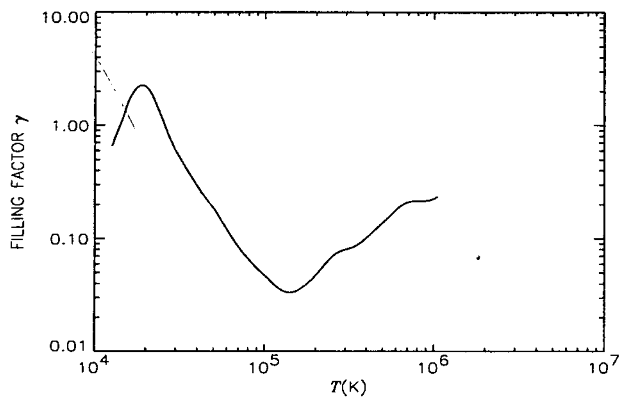

Fig. 4. Computed filling factor of "not-heated model" which accounts for the observed DEM.

in the real solar transition region.

One way of reducing the excess of DEM in "not-heated model" is to reduce the filling factor to less than unity with height (temperature). To examine the extent to which the filling factor affects DEM, we estimated the filling factor of the model by requiring that the computed DEM matches the observed one. The resulting filling factor is presented as a function of temperature in Figure 4. It is not surprising to see that some of the computed filling factor could exceed unity over a certain range (e.g., around 2×10^4 K), for we forced the computed DEM to be in agreement with the observed DEM. $\gamma>1$ means that some additional heating is needed along the flux tube. The needed heating is found to be at least 9.3×10^4 erg/cm^2/s between 1.3×10^4 K and 2.5×10^4 K. Above this region, the computed filling factor decreases to the minimum value of 0.03 at about 10^5 K. Considering expanding flux tube, this decreasing filling factor means substantial flux tubes are disappearing as loops.

However, the observed filling factors are 0.01 or less between 2×10^4 K and 2×10^5 K (Feldman, Doschek & Mariska, 1979, Dere et al., 1987). Although this value may increase by the factor of up to 8 (Judge, 2000), the filling factor may not exceed 0.1. To maintain the maximum filling factor as 0.1 in the lower transition region, substantially more heating would be needed than mentioned above and its distribution would similarly decrease as in the Figure 4. The source of heating is not yet clear. The heating rate for the MHD turbulence presented by Chae, Schuhle & Lemaire (1998) is far less than the required. Alfven waves satisfy the requirement but the wave should propagate downward. Still some other mechanism such as conductive heating across the field line may also play a role as shown in the 2-D static valley models by Mok & Van Hoven (1993) and Ji, Song, & Hu (1996). The perpendicular conductivity is very small usually but becomes comparable to the parallel one around 10^4 K. And the greater temperature gradient across the field line makes the perpendicular conductive heating significant. The solar atmosphere could be modeled as a forest of flux tubes surrounded by corona which supplies the heat to the roots of surrounding flux tubes via conductive heating across the field. To examine this we would need complete 3-D models which could reproduce the observed DEM and the Doppler shifts.

In summing up, we have considered two models, "not-heated model" and "filled-up model". We recognized that "filled-up model" faces a serious problem of having excessive conductive heating from the corona. It is extremely difficult to expel the excess of the conductive energy flowing downward from the corona in "filled-up model". However, "not-heated model" is capable of reducing the computed DEM to the observed DEM through adjustment of the filling factor by keeping it under unity. At the lower region, we can also match the computed DEM to the observed by providing some heating.

It may be concluded that some local heating is definitely needed for flux tubes along the transition region and the filling factor has to be incorporated into model computations. However, the problem still remains on how to obtain a realistic filling factor. The real nature of the solar transition region resides in somewhere between these two extreme cases. We hope that the pending problem will be resolved soon with the help of more elaborate solar UV and EUV observations in the immediate near future.

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