A UNIFIED MODEL FOR THE SUN'S LOWER AND UPPER TRANSITION REGIONS

H. S. Jr, M. T. SONG, AND F. M. HU
Purple Mountain Observatory, People's Republic of China
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ABSTRACT

In this paper, we present a self-consistent, unified model for the solar transition region (10^4 < T < 10^6 K). Motivated by Athay's conceptual model that the isothermal surfaces of the solar lower transition region are highly roughened, we construct a configuration of isothermal surfaces for the solar transition region in which the curvature of isothermal surfaces is assumed to decrease from the lower transition region to the upper transition region. The magnetic field is assumed to be vertical. Based on this picture, we demonstrate that the thermal structure of the entire solar transition region can be regarded as being determined by constant energy of combined conduction (parallel and perpendicular to the magnetic fields) transported across isothermal surfaces. After allowing the parameter \( \xi \), the ratio of the area of the curved isothermal surface to the area of the parallel plane, to decrease exponentially from approximately 800.0 at the bottom of the solar transition region to 1.0 in the upper transition region, the predicted differential emission measure curve can be in good agreement with the observation in the entire transition region provided that the decreasing coefficient is suitably chosen.

Subject headings: Sun: magnetic fields — Sun: transition region

1. INTRODUCTION

The solar transition region, sandwiched between the high-temperature corona and the cool chromosphere, is defined as a region which includes all gas in the temperature range \( \sim 10^4-10^6 \) K. Because of the observed valley-shaped curve of differential emission measure with temperature (Fig. 4), the transition region is divided into the lower transition region (\( \sim 10^4-10^5 \) K) and the upper transition region (\( \sim 10^5-10^6 \) K). The thermal structure of the upper transition region has been reasonably well understood with a plane-parallel model in which approximately constant conductive heat flux along magnetic field lines is assumed (Athay 1966, 1985; Moore & Fung 1972). However, this oversimplified model fails badly in attempting to explain the behavior of the lower transition region. A number of different proposals have been put forward to predict the run of differential emission measure of the lower transition region; a fully satisfactory model does not yet exist (Athay 1990).

It has become clear that the physical processes in the lower transition region are fundamentally different from that in the upper transition region. But what can it be when the temperature is near \( 10^5 \) K? Obviously, all parameters should change continuously from below \( 10^5 \) K to above \( 10^5 \) K. So, if we accept that the successful explanation for the behavior of the upper transition region is not just fortuitous, we will expect that any proposed models for the lower transition region should be comparable with the existing model for the upper transition region at \( T \sim 10^5 \) K, i.e., the existing model of constant conductive heat flux along magnetic field lines should serve as somewhat of a boundary condition for any proposed model of the lower transition region. Thus, when we think we have established a good model for the lower transition region, we still need to see whether this model can change into the model of the upper transition region when the temperature approaches a value of above \( 10^5 \) K. It is important for us to understand both regions in a unified model.

Rabin & Moore (1984) proposed a model that is based on local heating in the lower transition region by fine-scale filamentary electric currents along magnetic field lines. The energy heating the cooler plasma between the strands of electric currents is conducted across the magnetic field lines. In their model, they produced a distribution of emission measure over a temperature range \( \sim 10^4-10^5 \) K that is in good agreement with the observation. Nevertheless, in addition to the fact that the required narrow dimension for the electric currents cannot be observable, they did not show how the behavior of the energy transfer changes from perpendicular conduction in the lower transition region to parallel conduction in the upper transition region. Furthermore, the predicted emission for the lower transition region cannot connect smoothly the curve of the upper transition region predicted by the existing model of constant conductive heat flux along magnetic field lines.

Athay (1990) went further in his back-heating model with the simple explanation that the conductive heat flux from the corona \((1.0 \times 10^6 \text{ergs cm}^{-2} \text{s}^{-1})\) (Athay 1985) is sufficient to balance the observed total radiative losses in the entire transition region including Ly\( \alpha \) (Timothy 1977, Vidal-Madjar 1977). Based on Rabin's (1986) suggestion that energy is transported in the transition region through a combination of parallel and perpendicular conduction, he constructed a highly roughened isothermal surface with a checkerboard of cool peaks and hot valleys. Energy is transported along vertical magnetic field lines in hot valleys, and the energy in hot valleys is transported across the magnetic field lines into cool peaks. In the cool peaks, the energy is dissipated by means of radiation. By adjustment of parameters, Athay was able to predict the theoretical run of emission measure that is in good agreement with the observation. However, the predicted emission measure in his model becomes divergent when the temperature approaches \( 2.7 \times 10^4 \) K, at which point the heat flux of crossfield conduction vanishes.

In the present investigation, we also expand upon Rabin's suggestion (1986) and use Athay's (1990) conceptual model that the isothermal surfaces in the lower transition region is highly roughened. We want to present a unified model for the entire transition region by construction of a more real configuration of isothermal surfaces in which heat transfer can change smoothly from parallel conduction in the upper
transition region to perpendicular conduction in the lower transition region. The presentation of such a configuration is in § 2. In § 3, by assuming a heating function in the energy equation to balance the radiative losses, the divergence of the heat flux vector of combined parallel and perpendicular conduction is made to be zero everywhere. So the energy transported across any isothermal surface becomes constant. We find that the theoretical differential emission measure produced by this model can be in good agreement with the observation in the entire transition region.

2. GEOMETRIC CONFIGURATION OF THE TRANSITION REGION

Observations in the extreme-ultraviolet (EUV) show that the lower transition region is highly structured. Images in Lyα show structures such as spicule-like extensions and loops down to the limit of 1 or 700 km (Bonnet et al. 1980, 1982). The lower transition region resembles an Hα spicule more than it does a thin horizontal layer (Zirin & Dietz 1963; Feldman, Doschek, & Mariska 1979; Withbroe 1983). By presenting high resolution of spectroheliograms, Dere & Mason (1990) showed that the transition region consists of elongated structures. Thus, it will be a straightforward step to assume that the lower transition region is comprised of fine structures that are magnetically insulated from the corona and are spatially unresolved by existing observations (Rabin & Moore 1984). Cool features in the lower transition region can extend up into the upper transition region or corona, so the isothermal surfaces can be highly roughened. The existence of magnetic fields makes it possible for the energy transfer to be a combination of parallel and perpendicular conduction.

Based on the above observational results and Athay's model (1990), we propose a two-dimensional geometric configuration of isothermal surfaces for the transition region (Fig. 1). The magnetic fields are assumed to be vertical, and the curvature of the isothermal surfaces decreases upward until in the upper transition region isothermal surfaces become plane-parallel. From Figure 1, we can see that the energy transfer processes go gradually from parallel conduction in the upper transition region to a combination of parallel and perpendicular conduction until near the bottom of the lower transition region perpendicular conduction dominates. This is in agreement with our discussed principle above, i.e., we should understand both regions in a unified model without violating the existing successful model for the upper transition region. We expect that this picture of energy conduction processes can produce the observed valley-shaped differential emission measure curve of the whole transition region.

3. THEORETICAL DIFFERENTIAL EMISSION MEASURE

As a working picture, we simplify the curved isothermal surfaces shown in Figure 1 to sawtooth-shaped surfaces (Fig. 2). Figure 2 shows a vertical cross section of two simplified isothermal surfaces which correspond to temperature $T$ and $T + dT$, respectively. For each triangularly convex surface, the ratio of its area to the area of the horizontal planner surface can be given as

$$\xi = \sqrt{\left(\frac{H}{d_i}\right)^2 + 1}.$$  

(1)

We assume that $H/d_i$ is the same for every temperature level, and this assumption results in $\xi \sim \xi(T)$. Obviously, the value for $\xi$ in the upper transition region should be approximately 1.0.

The differential measure for a plane-parallel stratified atmosphere is defined by the equation

$$\epsilon(T) = n_e^2 \left(\frac{\Delta \ln T}{\Delta l}\right)^{-1},$$  

(2)

where $n_e$ is the electron density. For the isothermal surfaces shown in Figure 2, equation (2) should be replaced by the equation (Athay 1990)

$$\epsilon(T) = n_e^2 \xi(T) \left(\frac{\Delta \ln T}{\Delta l}\right)^{-1},$$  

(3)

where $\Delta l$ is measured normal to the surface and is the thickness of the layer in which $\Delta \ln T = 1.0$.

Here, in a static atmosphere, we can write the energy balance equation as

$$\nabla \cdot \mathbf{F} = \mathbf{L}(T) - \mathbf{H}(T),$$  

(4)

where $\mathbf{F}$ is the heat flux vector, and $\mathbf{L}(T)$ and $\mathbf{H}(T)$ correspond to the radiative loss function and heating function, respectively. We assume further that the heating term balances the radiative loss term in equation (4) at each temperature level. So, this results in a zero divergence of heat.
be given by the expression
\[ F_{T} = \sqrt{F_{\perp}^2 + F_{\parallel}^2} \]
\[ = \sqrt{\left(\frac{\kappa_{\perp} T^{-5/2}}{dT/dx}\right)^2 + \left(\frac{\kappa_{\parallel} T^{5/2}/dT/dz}{dT/dz}\right)^2}, \]
(7)
where \( F_{\perp} \) and \( F_{\parallel} \) are perpendicular and parallel components of the conductive heat flux vector, respectively. From Figure 2, we can see that \( dx = dl/\sin \theta, \ dz = dl/\cos \theta \). According to equation (1), the angle \( \theta \) can be given by
\[ \theta = \tan^{-1} \sqrt{\xi^2 - 1}. \]
(8)
So, we obtain
\[ \left(\frac{dT}{dl}\right)^{-1} = \frac{\xi}{F_{6.0}} \sqrt{\left(\frac{\kappa_{\perp} T^{-5/2} \sin \theta}{\cos \theta}\right)^2 + \left(\frac{\kappa_{\parallel} T^{5/2} \cos \theta}{\cos \theta}\right)^2}. \]
(9)
Combining equation (3) and equation (9), we finally obtain
\[ \epsilon(T) = P_{6.0}^2 \frac{\left(\frac{dT}{dl}\right)^{-1}}{F_{6.0}^2} T^{-1/2} \sqrt{\left(\frac{\kappa_{\perp} T^{-5/2} \sin \theta}{\cos \theta}\right)^2 + \left(\frac{\kappa_{\parallel} T^{5/2} \cos \theta}{\cos \theta}\right)^2}, \]
(10)
where \( \kappa_{\perp} \) (Athay 1990) and \( \kappa_{\parallel} \) can be given by
\[ \kappa_{\perp} = 2.0 \times 10^{-16} \frac{P_{6.0}^2}{B^2}, \]
\[ \kappa_{\parallel} = 1.0 \times 10^{-6}, \]
in cgs units (Spitzer 1962; Athay 1990).
For \( B = 2 \, \text{G}, \ P_{6.0} = 1.0 \times 10^{15} \, \text{cm}^{-3} \, \text{K}, \ F_{6.0} = 1.2 \times 10^6 \, \text{ergs cm}^{-2} \, \text{s}^{-1}, \) we finally obtain
\[ \epsilon(T) = 8.3 \times 10^{17} \xi^2 \times \sqrt{1.0 \times 10^{38} (T^{-7/2} \sin \theta)^2 + (T^{3/2} \cos \theta)^2}. \]
(11)
Now we have obtained a theoretical expression for the differential emission measure. The question remaining is how we define the function \( \xi(T) \). From the geometric configuration of isothermal surfaces constructed in Figure 1, we know that the value of \( \xi(T) \) must decrease when the temperature increases. Not losing generality, we assume
\[ \xi(T) = 1.0 + \xi_0 e^{-a(T - T_0)}. \]
(12)
The constant \( \xi_0 \) can be estimated roughly by letting \( T = T_0 \). Here we choose \( T_0 = 10^4 \, \text{K}. \) According to the observational results of \( \epsilon(T_0) \) (Raymond & Doyle 1981), \( \xi_0 \) is estimated as
\[ \xi_0 \sim 800.0. \]
Finally, it is only a simple work to adjust the parameter \( \alpha \) to make our predicted emission measure to be compared with the observation. From Figure 4, we can see that when \( \alpha \sim 8.0 \times 10^{-3}, \) our predicted emission measure is in good agreement with the observations.

4. DISCUSSION

We have demonstrated that a purely combined conduction model of the transition region can explain the differential emission measure of the entire transition region. It is a modification of the Athay (1990) model, and this model has a advantage of simplicity. It gives us a clear physical picture. While we are able to calculate the \( \epsilon(T) \) curve continuously throughout the entire temperature range, we have avoided the divergence problem which appeared in Athay's work.
By introducing curved isothermal surfaces, the very low conductive coefficient (both parallel and perpendicular) is compensated by the conduction area which has been greatly increased, and the volume contained in the temperature range $T \sim T + dT$ has also been increased. These two factors will both enhance the emission measure in the lower transition region. This is the essential point of this paper. Actually, it is the parameter $\xi$ which determines the values of $\epsilon(T)$ when the temperature is below $10^5$ K and more above $10^5$ K.

From equation (11), we can see that when the temperature approaches $10^4$ K, the perpendicular conduction dominates. Under such a circumstance, equation (11) gives $\epsilon(T) \sim T^{-7/2}$. Nevertheless, when the temperature approaches the values of the upper transition region, the perpendicular conduction will soon be replaced by parallel conduction, which gives $\epsilon(T) \sim T^{-3/2}$.

While we have successfully predicted the differential emission measure for the entire transition region, we have not given any convincing argument for an unknown heating function to balance radiative losses at every temperature level. This is just an assumption. Actually, we only need the heating function to balance roughly the radiative loss function at any given temperature. This rough balancing results only in some small positive or negative amounts of the divergence of the heat flux function, and this will cause the heat flux $F_P$ to increase or reduce a little, which should not affect the theoretical emission measure distinctly.

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