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On the Classic Heat Conduction in the Chromosphere-Corona Transition Region of the Solar Atmosphere

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Abstract—The distribution of the temperature versus the thickness in the chromosphere-corona transition region of the solar atmosphere on the assumption that the plasma heating by classical heat flux is balanced by the energy loss by radiation. It is shown that the transition region between the corona and chromosphere is a thin layer, to which, however, a simple collision approximation may be applied.

Keywords: Sun, chromosphere, corona, transition region, thermal conductivity.

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INTRODUCTION

An increasing number of articles are appearing that suggest that the chromosphere–corona transition region of the solar atmosphere should be considered in the collisionless approximation. Moreover, it is argued (e.g., in [1, 2]) that the thickness of the transition region is supposedly much smaller than the mean free path of thermal particles, and the separation of the solar plasma into two phases (high-temperature with the electron temperature of $T_e \gtrsim 10^6$ K and low-temperature, $T_e \lesssim 10^4$ K) is due to the excitation of ion-acoustic turbulence. This conclusion is extended to the two-phase character of the space plasma in general.

The established representations of the transition region between the corona and the chromosphere as the layer where heating by the classical heat flux from the corona into the chromosphere is balanced by energy losses by radiation are being questioned for the following reasons. Firstly, early estimates of the transition layer, even the most accurate ones (e.g., [3]), were based on very approximate calculations of the power of energy loss by radiation of optically thin plasma with the cosmic abundance of elements [4]. Secondly, modern observations of the chromosphere show a high degree of nonstationarity. This raises the question of whether it always exists [5]. Another question is that of whether it is possible to consider a transition layer as a stationary phenomenon.

In this paper we solve the one-dimensional balance equation between the heating by the heat flow under the assumption of classical electron heat conduction and the cooling of plasma by its radiation; we used the results of modern calculations of the power of energy loss. This solution confirms the separation of the solar plasma into high and low temperature plasma due to the specific dependence of the function of radiative cooling on temperature, namely, due to the presence of several fairly sharp peaks. In plasma with the cosmic abundance of elements, such peaks are due to the radiation of a small admixture of helium and heavier ions. The obtained solution shows that the characteristic plasma thickness of the transition region is much greater than the thickness corresponding to the mean free path of thermal electrons. Thus, it is obvious that the collisionless approximation may not be applied to the transition layer. In Section I, the dependence of the temperature T on the thickness ξ is found. The comparison of the depth of the transition layer with the mean free path is given in Section II. The results are summarized in the Conclusions.

1. THE CALCULATION OF THE TEMPERATURE DEPENDENCE ON THE PLASMA THICKNESS

Let us consider two processes in the solar plasma, i.e., the heating by a heat flux from the corona into the chromosphere and the cooling radiation.

As the origin of the coordinate system, we choose the point 0 with the temperature $T_0 = 10^6$ K, located in the upper part of the chromosphere–corona transition region between the corona and chromosphere. The axis of x is directed downward along the radius of the Sun. Let us denote the concentration of plasma particles in the point x by $n(x)$, measured in cm^{-3}. Now, we determine the material thickness ξ in the point with coordinate x as

$$\xi = \int_0^x n(x)dx, \ \text{cm}^{-2}. \qquad (1)$$

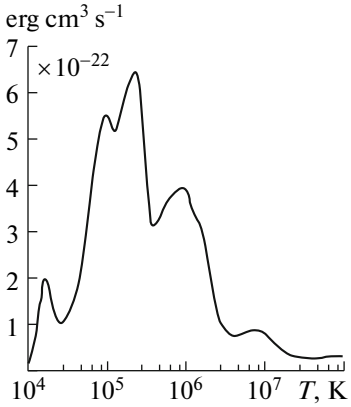

Fig. 1. The dependence of the radiative energy loss function on the temperature $L = L(T)$.

We assume that the plasma is in local thermodynamic equilibrium and is characterized by the temperature $T(x)$ of the plasma at the point with coordinate x. We are interested in the dependence of $T = T(\xi)$ on the temperature of the thickness of the transition layer between the corona and chromosphere. In this case, we assume that in the absence of heat flux from the corona into the chromosphere some other mechanism of heating of the chromosphere supports its time-independent temperature, which is denoted by T_∞. Strictly speaking, T_∞ also depends on x. However, in this problem it is enough to accept that T_∞ is equal to a constant value, i.e., a temperature at the base of the transitional layer, such as 10^4 K.

The range of temperatures $T \gtrsim 3 \times 10^4$ K is of the greatest interest to us; a huge amount of modern spacecraft observational data exists for this range (e.g., see [6, 7]). In this region, the effects of the radiation absorption and thermal conductivity of neutrals become negligible.

Let us estimate the characteristic times of collisional relaxation [8, 9] in the transition layer at a temperature of $T \approx 10^5$ K. Assuming that the plasma concentration in the transition layer at this temperature and the concentration of plasma in the corona $n_{cor} \approx 2 \times 10^8$ cm^{-3} at the coronal temperature of $T_{cor} \approx 2 \times 10^6$ K are coupled by the condition of constant pressure, we find the characteristic time of electron collisions in the transition layer $\tau_{ee} \sim 4 \times 10^{-4}$ s. For the proton component of plasma this is $\tau_{ep} \sim 4 \times 10^{-3}$ s. Finally, the characteristic time of energy exchange between electrons and protons is $\tau_{ep} \sim 10^{-1}$ s. If the heat source is small flares (microflares) with the duration of $\tau_f \gtrsim (1-10)$ seconds associated with the magnetic reconnection in the lower corona, then taking the characteristic time of heating to by $\tau_h \sim \tau_f$, we conclude that this time is sufficient for distributions to become close to the Maxwell distribution for the electron and proton components of the plasma. Moreover, with a good degree of accuracy, $T_e = T_p = T$.

Under these conditions values of T and ξ are related to the considered physical processes by a simple equation of energy balance [3]:

$$n\frac{d}{d\xi}\left(\kappa n\frac{dT}{d\xi}\right) = L(T)n^2 - P_\infty. \quad (2)$$

Here κ is the electronic thermal conductivity. The proton thermal conductivity, compared with it, is negligible (e.g., see [10]). $L(T)n^2 = P(T, n)$ is the radiation power per unit volume of plasma. In the collisional excitation of levels, it is proportional to the concentration of n (cm^{-3}). The function $L(T)$ describes the dependence of energy loss by radiation on the temperature, as shown in Fig. 1. This is called the radiative loss function. $P_\infty = L(T_\infty)n^2$ is the power of the stationary heating of the chromosphere by an "external" source, in particular, by the flow of waves from the convection zone.

Parameters κ, L, and P in Eq. (2) are known. Neglecting the thermal conductivity of neutrals, we have the classical formula [8, 9] for the electronic conductivity

$$\kappa \approx \frac{1.84 \times 10^{-5}}{\ln\Lambda} T^{5/2}. \quad (3)$$

In the Coulomb logarithm

$$\Lambda = \begin{cases} 1.24 \times 10^4 T^{3/2}/n^{1/2}, & T < 5.8 \times 10^5 \text{ K}, \\ 9.44 \times 10^6 T/n^{1/2}, & T \geq 5.8 \times 10^5 \text{ K}. \end{cases}$$

The dependence $L = L(T)$ is taken from the results of calculations performed at the Astrophysical Institute Potsdam using the system of atomic data and CHIANTI programs (version 5.2), developed in the framework of international cooperation involving NRL (USA), RAL (UK), MSSL (UK), Universities of Florence (Italy), Cambridge (UK), and George Mason University (USA) (http://www.chiantidatabase.org/). The constantly updated base of atomic data and CHIANTI programs for the calculation of spectra takes the atomic energy levels, the probabilities of radiative transitions, different rates of recombination (including dielectronic recombination) and ionization for different atomic levels, data on collision cross sections for a large number of ions, and much more, into account (see [6, 11]). Radiative loss function that we use is a modern international standard in studies of solar physics.

To define the dependence $n = n(T)$ without solving the full system of hydrodynamic equations, we consider the opposite limiting cases of fast (pulse) and slow (stationary) heating by the heat flow separately [3], see also 2.2.1 in [12]. For the case of such rapid heating that the plasma density does not have time to change (n = const), we set $n = n_\infty$, i.e., in the dimensionless form $n = 1$. In the case of such slow heating that the pressure is equalized (p = const), and since $p = nk_vT$, then $n = p/k_vT$ or in the dimensionless form

$$n = \frac{1}{T}. \quad (4)$$

Let us solve the balance Eq. (2) for the boundary conditions

$$\left.\frac{dT}{d\xi}\right|_{\xi\to\infty} = 0, \quad T|_{\xi=0} = T_0. \quad (5)$$

We substitute the value of heat flux

$$F = -\kappa n\frac{dT}{d\xi}. \quad (6)$$

in Eq. (2) and multiply both sides by $\kappa dT/d\xi$. After simple transformations we obtain the desired expression for the heat flux in terms of radiative cooling

$$F = \left(\int_{T_\infty}^{T} 2(L(T') - L(T_\infty))\kappa n^2 dT'\right)^{1/2}. \quad (7)$$

So instead of a second-order differential Eq. (2) we have a system of two equations (7) and (6) of the first order for the heat flux F.

Let us rewrite Eq. (7) in the dimensionless form. To do this, we multiply it by

$$\frac{\xi_\infty^2}{n_\infty^2\kappa_\infty T_\infty L(T_\infty)},$$

where ξ_∞, n_∞, T_∞ and κ_∞ are units of measurement for the thickness, density, plasma temperature, and electron thermal conductivity, respectively. We obtain

$$F(T) = \left(\int_1^T 2K_1(L(T') - 1)\left(\frac{(T')^{5/2}}{\ln\Lambda}\right)n^2 dT'\right)^{1/2}, \quad (8)$$

where in the Coulomb logarithm

$$\Lambda = \begin{cases} 1.24\times10^4(TT_\infty)^{3/2}/(nn_\infty)^{1/2}, \\ T < 5.8\times10^5\ \text{K}, \\ 9.44\times10^6(TT_\infty)/(nn_\infty)^{1/2}, \\ T \geq 5.8\times10^5\ \text{K}, \end{cases}$$

and the coefficient

$$K_1 = \frac{\xi_\infty^2 L(T_\infty)\ln\Lambda_\infty}{\kappa_\infty T_\infty}.$$

We choose characteristic values to be

$$T_\infty = 10^4\ \text{K}, \quad n_\infty = 10^{10}\ \text{cm}^{-3}$$

then

$$\xi_\infty = n_\infty l_\infty = 3.15\times10^{15}\ \text{cm}^{-2},$$
$$l_\infty = \left(\frac{\kappa_\infty T_\infty}{L(T_\infty)n_\infty^2}\right)^{1/2} = 3.15\times10^5\ \text{cm} \quad (9)$$

are the characteristic values and at the same time the units of measurement of the thickness and length.

Let us transform Eq. (6) to the form

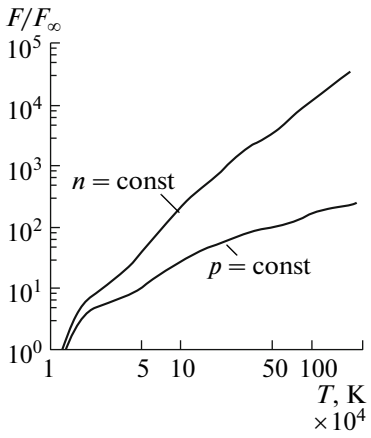

Fig. 2. The dependence of the heat flux on the temperature of $F = F(T)$ for the cases of fast (n = const) and slow (p = const) heating.

$$\xi = \int_T^{T_0}\kappa n\frac{dT}{F(T)}, \quad (10)$$

where $T_0 = 10^6$ K if $\xi = 0$.

Thus, the system of equations (7) and (6) is reduced to (8) and (10). Integrating (8), we obtain the dependence $F = F(T)$ shown in Fig. 2. Here the unit of measurement of the heat flow is

$$F_\infty = \frac{\kappa(T_\infty, n_\infty)n_\infty}{\xi_\infty} = 425\ \text{erg/s}.$$

Substituting $F(T)$ in (10), we find the desired dependence $\xi = \xi(T)$, i.e., the temperature distribution over the thickness of the plasma. The result is shown in Fig. 3.

2. TRANSITION REGION THICKNESS

The classical theory of thermal conductivity [8, 9] is applicable if the mean free path of thermal electrons is

$$\lambda_e \ll l_T = \frac{T_e}{|\nabla T_e|}. \quad (11)$$

Here l_T is the characteristic length scale for the temperature profile. Naturally, it depends on the temperature. Below for scale of l_T we take the distance, at which the temperature changes by an order of e.

Let us rewrite (11) as

$$\delta\xi \gg \xi_e, \quad (12)$$

where

$$\delta\xi(T) = \frac{d\xi(T)}{d\ln(T)} \quad (13)$$

is the temperature-dependent characteristic plasma thickness for the equilibrium temperature distribution $T = T(\xi)$ that we calculated and the thickness corresponding to the mean free path of thermal electrons is

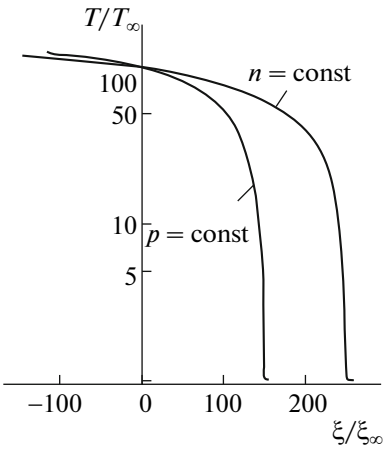

Fig. 3. The dependence $T = T(\xi)$ for the cases of fast (n = const) and slow (p = const) heating.

$$\xi_e = n_e\lambda_e = \frac{k_B^2 T^2}{\pi e^4 \ln\Lambda}. \quad (14)$$

Figure 4 shows the dependence $\delta\xi = \delta\xi(T)$ for the limiting cases of n = const and p = const. The dependence $\xi_e = \xi_e(T)$ is also shown.

As seen from Fig. 4, the condition $\delta\xi \gg \xi_e$ is satisfied at all temperatures corresponding to the transition region; for example, at the temperature 10^5 K, the transition layer depth is 35 km and the mean free electron path is 70 m. The characteristic thickness at which the temperature changes is 500 times greater than the thickness corresponding to the mean free path of electrons. In the transition to lower temperatures the layer becomes even thinner, but the condition of applicability of the classical heat conduction in it holds with even greater margin. Consequently, the chromosphere–corona transition region should be considered in the collisional approximation.

CONCLUSIONS

In this paper we found the equilibrium temperature distribution with the plasma thickness in the transition region between the corona and chromosphere of the Sun, assuming that the thermal conductivity is caused by thermal plasma electrons and at each point of the distribution the balance holds for heating by the classical heat flux and plasma energy loss by radiation. These results imply that the transition region between the corona and chromosphere should be considered in the *collisional* approximation, since the characteristic thickness over which the temperature changes is much greater than the thickness corresponding to the mean free path of thermal electrons.

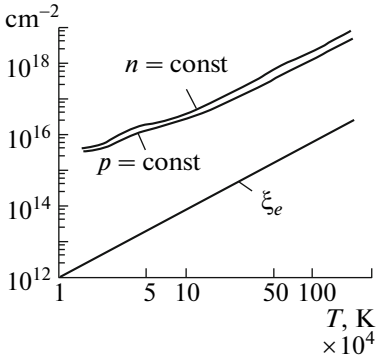

Fig. 4. Temperature dependence of the characteristic thickness $\delta\xi = \delta\xi(T)$ of the heated plasma for equilibrium temperature distribution for the fast (n = const) and slow (p = const) heating regimes. $\xi_e = \xi_e(T)$ is the thickness corresponding to the mean free path of electrons.

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