Applicability of the Classical Heat Conduction in the Solar Chromosphere-Corona Transition Region

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Since classic work due to Shmeleva and Sirovatsky [1] the corona-chromosphere transition region was usually considered in classical collisional approximation. However, in 1983 this approach was questioned by Shoub [2].

What are the main reasons of problems concerning applicability of the classical collisional approximation? One reason is that early studies of the transition region were based on not very precise calculations of the radiative energy loss function of optically thin plasma with the cosmic abundance of elements. Another reason is that modern satellite observations of the solar chromosphere show a high degree of nonstationarity [3]. In this regard the questions about the very existence of the chromosphere and the possibility of considering the transition region as being stationary arise. Thus, it is necessary to prove applicability of classical collisional approximation in the transition region, using new data of the radiative energy loss function of optically thin plasma with the cosmic abundance of elements and compare the result with observations.

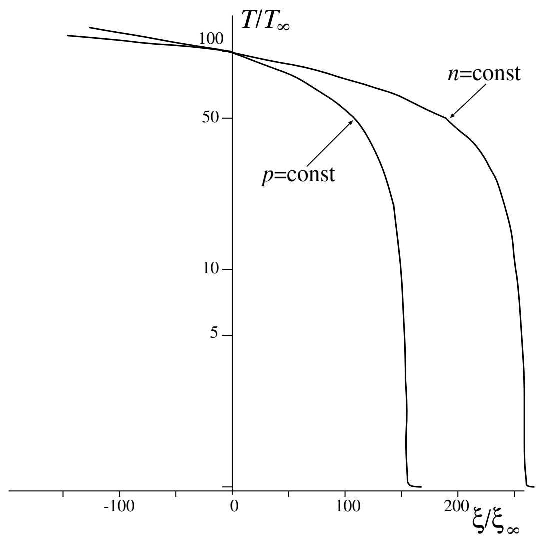

Figure 1: The dependence $T = T(\xi)$ for the cases of fast ($n = const$) and slow ($p = const$) heating. $\xi_\infty = 3.15 \times 10^{15}\,\mathrm{cm}^{-2}$, $T_\infty = 10^4$K.

The calculation of the temperature versus thickness dependence

In the magnetic tube we solve equation of balance between plasma heating by classical heat flux and the energy loss due to radiation:

$$\frac{d}{dx}\left(\kappa\frac{dT}{dx}\right) = L(T)\,n^2 - P_\infty\,. \tag{1}$$

Here κ is the coefficient of thermal conductivity. Neglecting the thermal conductivity of neutrals, we have the classical formula for the electron conductivity $\kappa = \kappa_0 T^{5/2}$ [4].

The radiation power per unit volume of plasma is $L(T)n^2 = P(T,n)$, where the function $L(T)$ is the radiative loss function, which describes the dependence of energy loss due to radiation on the temperature. $P_\infty = L(T_\infty)n^2$ is the power of the stationary heating of the chromosphere by an "external" source, partially, by the flux of waves from the convection zone. The dependence $L = L(T)$ is taken from the results of calculations [5] performed at the Potsdam Astrophysical Institute using the system of atomic data and CHIANTI programs (version 5.2). To define the dependence $n = n(T)$ without solving the full set of hydrodynamic equations, we consider two opposite limiting cases of pulse ($n = const$) and stationary ($p = const$) heating by the heat flow separately.

The computed temperature distributions [6] along the depth $\xi = \int_0^x n(x)\,dx$ are shown in Fig. 1. As seen from Fig. 1, plasma is divided into high and low temperature parts, and this result does not depend on the heating regime.

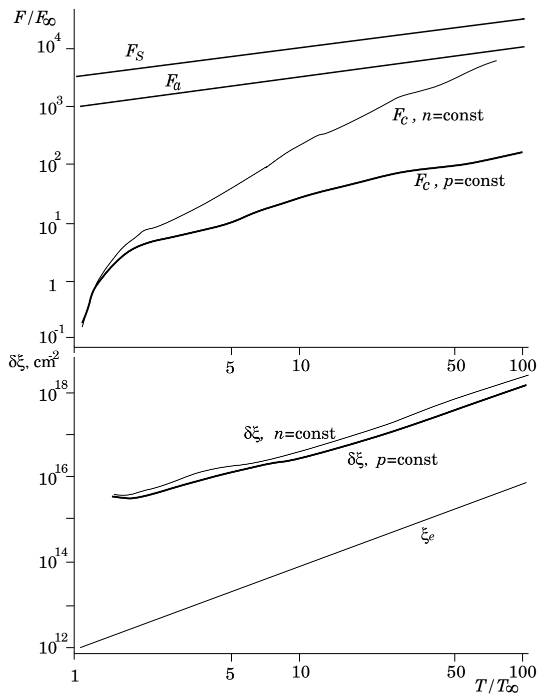

Figure 2: Temperature dependences of thermal fluxes, thicknesses, corresponding to characteristic scale of the temperature distribution and mean free path of the thermal electrons.

Applicability of classical collisional approximation

Classical collisional heat conduction [4] is valid if the following two conditions are satisfied:

$$\lambda_e < l_T \equiv T_e/|\Delta T_e| \tag{2}$$

and

$$F_c < min(F_s, F_a). \tag{3}$$

Here λ_e is the mean free path of the thermal electrons, l_T is the characteristic scale of the temperature distribution, F_c is the classical heat flux $F_c = -\kappa\, n\, dT/d\xi$, which is due to electron collisions. F_s and F_a is saturated and anomalous fluxes, respectively.

As it is seen from Fig. 2 the thickness, corresponding to characteristic scale of the temperature distribution $\delta\xi$ significantly exceeds the thickness, which is corresponding to the mean free path of the thermal electrons ξ_e. For example, at the temperature 10^5 K: $\delta\xi \approx 3\times10^{16}$cm^{-2} (35 km), and $\xi_e = 8\times10^{-13}$cm^{-2} (70m). It can also be seen that the classical heat flux is lower than the anomalous and saturated fluxes. Thus, the applicability conditions are satisfied in both regimes.

Stability of the obtained temperature distributions

From Fig. 3 one can compare temperature dependencies 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 with critical thicknesses ξ_{cc}, ξ_{cw} which correspond to the boundary of the region of the condensation and wave thermal instability modes, respectively. ξ_{cc}, ξ_{cw} are such that instabilities with smaller thicknesses are stabilized through thermal conduction.

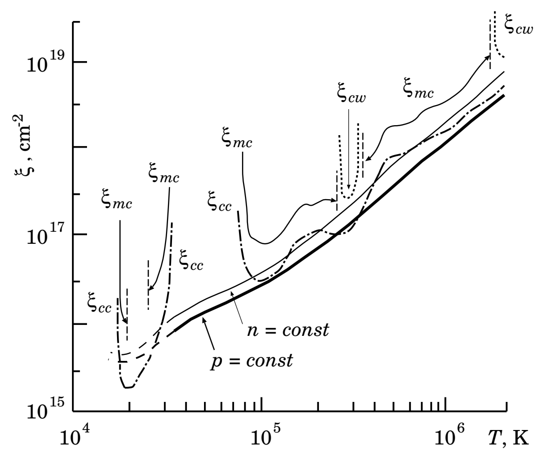

Figure 3: Temperature dependences of the characteristic thickness $\delta\xi = \delta\xi(T)$ of the heated plasma for the two regimes and critical instability thicknesses.

One can see that curves, which correspond to the characteristic thickness of the heated plasma for equilibrium lie lower than curves ξ_{cc}, ξ_{cw} practically in all temperature range. Only two temperature regions may seem to cause troubles. One of these regions is the $T \approx 2\times10^4$ K region. Checking the optical thickness at this temperature range, one can conclude, that approximation of optically thin plasma cannot be used here. One should solve the transition equation, which has been done carefully in [8]. So, there is no need for us to consider this region. Another nontrivial region is the temperatures greater than 10^5 K. Here the curve ξ_{cc} lies between curves, which correspond to the characteristic thickness of the heated plasma for equilibrium temperature distribution, within the accuracy of our calculations (and even more so within the accuracy of the CHIANTI calculations, bearing in mind the uncertainty related to the abundance of elements, etc.). It means that the temperature distribution is stable in this temperature region and is defined by the condensation instability.

Therefore the temperature distributions are stable in the temperature range considered ($3\times10^4 < T < 10^6$ K) [7].

Equilibrium profile emission

Our results allow us to compute the differential emission measure $DEM(T)$ of the plasma in the transition region. The theoretical dependence $DEM(T)$ was compared with the observations, which were taken by the SUMER instrument on board of SOHO on 20 April 1997 [3]. The result of this comparison is shown in Fig. 4. One can see that: (i) the observed points are located between two theoretical limits of fast and slow heating, (ii) the observations are closer to the curve corresponding to the slow ($p = const$) heating.

So, the heating regime is rather close to the slow one in the transition region of the quiet sun. And what is the most important, the classical collisional approach is valid, because results obtained in this approach agree with observational data.

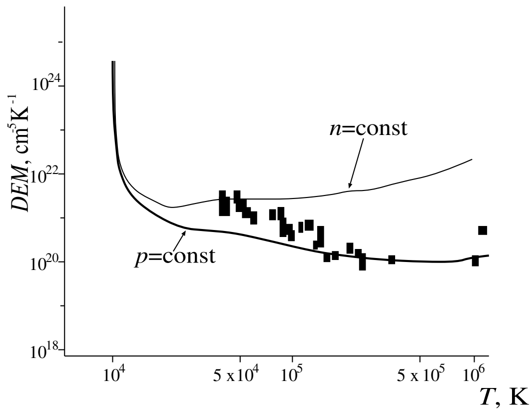

Figure 4: The theoretical DEM(T) dependence for the cases of fast ($n = const$) and slow ($p = const$) heating. The points correspond to observations by SUMER/SOHO 1997 [3].

Conclusions

In the magnetic tube the distribution of the temperature versus the thickness and emission measure in the solar chromosphere-corona transition region was obtained on the assumption that the plasma heating by classical heat flux is balanced by the energy losses due to radiation. Obtained temperature distribution is stable in the temperature range considered. The emission measure obtained from our temperature distribution shows a good agreement with observations.

The transition region between the corona and the chromosphere is a thin layer, to which, however, a classical collisional approximation may be applied. In the chromosphere-corona transition region of the quiet Sun regime of heating is close to the slow heating regime, in which gas pressure reaches equilibrium ($p = const$). It is also shown that obtained temperature distribution is a stable consequence of the thermal instability in the condensation mode regime.

References

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