THERMAL CONDUCTION IN THE TRANSITION REGION AND ITS EFFECTS ON THE ENERGY BALANCE OF OPEN CORONAL REGIONS

R. Hammer

Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany

Abstract

Thermal conductive energy flow into the transition region represents a considerable energy loss for the solar corona. Inclusion of this term lead to a new class of self-consistent models for magnetically open coronal regions. Recently a number of modifications of the thermal conductivity term were suggested, mainly in order to account for the emission measure reversal in the lower transition region. These suggestions include the contributions by ions and neutrals to thermal conduction, ambipolar diffusion, and turbulence. We show that diffusion, since it affects only the lowermost parts of the transition region, does not significantly change the global properties of the corona, unless the transition region base pressure is chosen unrealistically small. This behavior is explained in terms of the boundary layer character of the lower transition region in such models. By contrast, turbulence can enhance the conductivity more drastically and up to higher temperatures. For large and intermediate pressures, turbulent conduction tends to flatten the lower, but to steepen the remainder of the transition region. The overall thickness of the transition region is reduced, but the total energy losses are enhanced compared to models based on the Spitzer conductivity. The minimum possible energy losses of the corona are also enhanced. The coronal temperature that minimizes the energy losses, however, does not depend much on the type of conductivity.

1. Introduction

Magnetically open coronal regions lose energy by three mechanisms: (a) radiation from the corona, (b) wind, and (c) thermal conduction into the transition region. While (b) and (c) can be shown to increase with increasing coronal temperature T_c, (a) decreases. Therefore, there exists a certain coronal temperature $T_{c,min}$ that minimizes the total coronal energy losses F_L for a given base pressure p_0 (Hearn 1975).

Conduction into the transition region (term b) is an important energy loss for the corona. This term has often been neglected in solar wind models. By including it, however, the arbitrariness due to unknown lower boundary conditions is removed, and the corona models become self-consistent (*e. g.*, Couturier et al. 1979, Hearn and Vardavas 1981, Hammer 1982, Withbroe 1988, Hollweg 1992, Wang 1993).

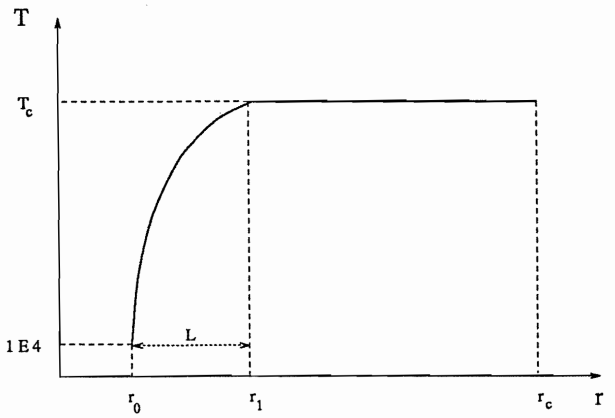

Fig. 1. A simple model of transition region and corona

Downward conduction, $F_C = -\kappa \nabla T$, serves to heat up the outflowing solar wind and to balance the radiation from the lower transition region (where the density and thus the emissivity is largest). In the corona, thermal conduction is dominated by electrons, for which the thermal conductivity $\kappa \propto T^{5/2}$. As a result of this strong temperature sensitivity, ∇T must become very large at low temperatures in order to maintain a sufficient energy flux F_C. Due to this steep temperature gradient, there is not much plasma left at a given temperature, in contradiction to the large observed emission measure at temperatures below about $2\,10^5$ K.

To resolve this discrepancy, a number of authors suggested geometric, time dependent, or opacity effects, which will not be discussed here. Others noticed that the classical electron conductivity is no longer appropriate at low temperatures, but that ions and neutral particles transport both translational and ionization energy, thus enhancing the conductivity. The transition region might even be turbulent, resulting in an even larger enhancement of κ. Then ∇T needs no longer be so steep to transport the energy, so that there would be enough plasma at low temperatures to explain the large emission measure.

The current paper uses a simple corona model (Sect. 2) to investigate the effects of such modifications of the thermal conductivity in the transition region on the corona and its minimum energy loss (Sect. 3).

2. Model

Since the details of the coronal heating law are not yet known, we consider a simple spherically symmetric model consisting of an isobaric ($p = p_0 =$ const), unheated transition region that is connected at radius $r = r_1$ to an isothermal ($T = T_c =$ const) corona (Fig. 1).

The total energy losses F_L can be calculated by integrating the radiative, conductive, and wind losses from the base point r_0 out to the critical point r_c. These losses are balanced by some kind of nonthermal heat input, which is absorbed in the corona over a characteristic damping length L of the order of the distance $r_1 - r_0$. The model is uniquely determined by specifying two quantities, *e. g.* p_0 and T_c, or F_L and L.

Calculations were made for four different types of conductivity, which are shown in Fig. 2 for a pressure of 0.1 dyn cm^{-2}:

- the canonical Spitzer-Härm (1953) electron thermal conductivity in the fully ionized limit,
$$\kappa = \frac{1.89\,10^{-5}}{\ln\Lambda} T^{5/2},$$
where the Coulomb logarithm $\ln\Lambda$ is a slowly varying function of T and n_e;

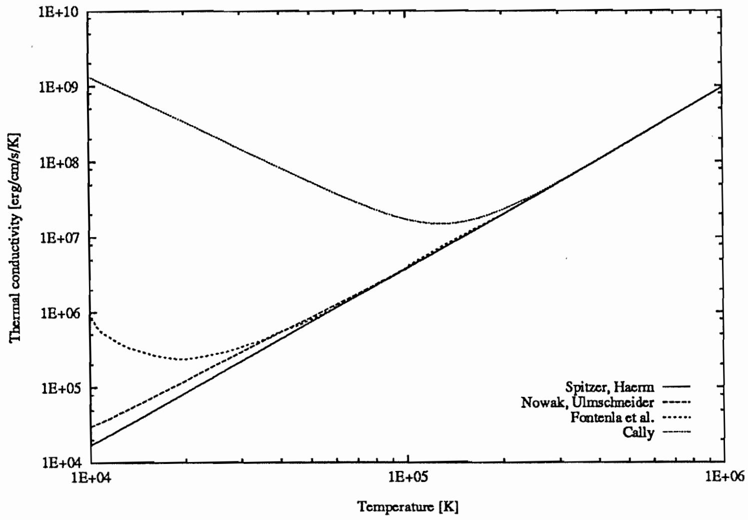

Fig. 2. Thermal conductivity *vs.* temperature for a pressure of 10^{-1} dyn cm^{-2}.

- the conductivity published by Nowak and Ulmschneider (1977). It is based on numerical fits to a full Chapman-Enskog-Burnett solution that takes the mutual interactions between various species into account. The contribution by neutrals and the transport of ionization energy lead to an enhancement of κ with respect to the Spitzer value. (For the pressure and ionization model used in Fig. 2, however, the difference is largest at $T < 1\,10^4$ K and thus not prominent in the figure.)

- the conductivity derived by Fontenla et al. (1991; their Fig. 7) from hydrostatic energy balance models of the transition region that take into account the diffusion of hydrogen atoms and ions;

- the turbulent conductivity postulated by Cally (1990). He followed the suggestion by various authors (*e. g.* Heyvaerts and Priest 1983, 1992) that the transition region might be in a permanent state of turbulence. For the associated turbulent conduction Cally assumed a mixing length type law,

$$\kappa_{turb} = \phi \rho c_p u l,$$

where the eddy speed u is taken from the observed nonthermal velocities, the mixing length l is parametrized as a power law in T, and the power law exponent as well as the coefficient ϕ are adjusted such that the model gives the observed emission measure distribution. For the total conductivity Cally took the sum of κ_{turb} and the Spitzer value. Note that κ_{turb} is proportional to the density and thus much more strongly dependent on p than the other κ variants.

3. Results

Corona models calculated with the Fontenla et al. and (even more so) with the Nowak and Ulmschneider conductivities are barely distinguishable from those calculated with the Spitzer κ. For example, the total energy losses F_L and the thickness $r_1 - r_0$ of the transition region for given parameters p_0 and T_c, and the minimum possible energy loss $F_{L,min}$ for given p_0, differ between the models by at most 1 % as long as p_0 is large or intermediate.

Significant deviations exist only for extremely small values of the base pressure. Here the thickness of the transition region turns out to be larger, and the total energy losses smaller, than with the Spitzer conductivity, by an amount of the order of 30 % for 10^{-3} dyn cm^{-2} with the Fontenla et al. conductivity and 10^{-4} dyn cm^{-2} with the Nowak and Ulmschneider conductivity. This can be explained by the fact that for such unrealistically small base pressures the total emission is small, thus the temperature gradient required to transport the heat flow becomes so flat that stratification is important already at low temperatures. As a result, most of the plasma resides at low temperatures, where the conductivities deviate significantly from the Spitzer value.

For larger base pressures, on the other hand, only little plasma exists at these low temperatures. This explains why corona models are found to be very insensitive to whatever happens below, say, 10^5 K. It has been known for a long time that models of the transition region and corona are insensitive to the temperature and its derivative at the base of the transition region. Gonczi et al. (1977; see also Appendix A of Hammer 1982) explained this insensitivity by showing that the lower transition region acts as a mathematical boundary layer over which any knowledge of the actual boundary value is rapidly lost.

By contrast, Cally's turbulent conductivity differs significantly from the Spitzer value up to higher temperatures. Since it is proportional to the density, the difference is even larger than shown in Fig. 2 for $p_0 > 10^{-1}$ dyn cm^{-2}. Our calculations show that for large p_0 the thickness of the transition region is by nearly an order of magnitude smaller than in the same model calculated with the Spitzer conductivity, while the total radiation is larger by a similar factor. This can be explained as follows. At low temperatures κ_{turb} is so extremely large that the temperature gradient becomes flat at low temperatures, so that a lot of plasma exists there and radiates efficiently. In order to supply this large amount of energy through the *upper* transition region, where Cally's conductivity does not differ from the Spitzer value (cf. Fig. 2), the temperature gradient must be much steeper. As a result, the overall thickness of the transition region becomes smaller than in the Spitzer case. Therefore the main effect of turbulent conductivity is to flatten out, and to produce a large amount of radiation from, the lower transition region, while the upper transition region steepens.

With decreasing pressure, the turbulent conductivity decreases, and so do the deviations from models using the Spitzer conductivity. The ratio $(r_1 - r_0)_{\mathrm{Cally}}/(r_1 - r_0)_{\mathrm{Spitzer}}$ of the thicknesses of the transition regions, for example, is typically 1/10, 1/5, 1/2, and 2 for $p_0 = 1$, 10^{-1}, 10^{-2} and 10^{-3} dyn cm^{-2}. The inverse of the ratio of the total energy losses, $F_{L,Cally}/F_{L,Spitzer}$, varies similarly, as do the minimal possible energy losses. Remarkably enough, however, the coronal temperature $T_{c,min}$ that minimizes the energy losses does not differ much between the Cally and Spitzer models.

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