EFFECTS OF AMBIPOLAR DIFFUSION ON
PROMINENCE THREAD MODELS

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Abstract. We have improved previous model calculations of the prominence-corona
transition region including the effect of the ambipolar diffusion in the statistical
equilibrium and energy balance equations. We show its influence on the different
parameters that characterize the resulting prominence theoretical structure. We take
into account the effect of the partial frequency redistribution (PRD) in the line profiles
and total intensities calculations.

Key words: Sun – Prominences – Radiative Transfer – Ambipolar Diffusion

1. Introduction

Many authors, see, e.g., Heasley and Milkey (1983) or Gouttebroze et al. (1993) de-
veloped non-LTE one dimensional models of solar prominences based on radiative
equilibrium or on a temperature structure arbitrarily specified.

However, the evidence of a fine structure in prominences was pointed out by many
authors (Dunn 1960, Engvold 1976, Zirker and Koutchmy 1990, Mein and Mein 1991,
Heinzel and Vial 1992). Prominences appear as aggregates of a great number of small
threads whose size and dimensions are not completely resolved.

Taking into account energy balance, Fontenla and Rovira (1985) developed thread
models for the prominence-corona transition region (PCTR). They solved the radia-
tive transfer, statistical equilibrium and ionization equilibrium equations simultane-
ously, assuming a three level hydrogen atom plus continuum. They also computed the
energy balance equations including the hydrogen radiative losses obtained from their
calculations, the Cox and Tucker (1969) radiative losses for other elements, and heat
conduction. They replaced a single thread by a symmetrical slab with a plane-parallel
gammaetry and illuminated by the underlying atmosphere.

The significance of the ambipolar diffusion (AD) – the diffusion of H atoms with respect to protons and electrons – in theoretical models of the chromosphere-corona transition region has been demonstrated by Fontenla et al. (1990, 1991) who showed how it controls both energy transport and radiative losses.

Our present results show that ambipolar diffusion is also significant for the PCTR.

2. The Ambipolar Diffusion in the PCTR

We have modified the numerical code developed by Fontenla and Rovira (1985) to include this effect. We have solved the following energy equation (Fontenla et al., 1990):

\[
\frac{d}{ds}[U(5/2p - E_H n_1) - (5/2kT + E_H)n_p n_1/(n_p + n_1)V_A + F_C] = \\
= Ud\rho/ds - \int(\eta_\nu - \chi_\nu l_\nu)d\omega d\nu
\]

where \(U\) is the mass velocity, \(p\) is the pressure, \(k\) is the Boltzmann constant, \(T\) is the temperature, \(E_H\) and \(n_1\) are the ionization energy and the number density of hydrogen atoms, respectively, \(n_p\) is the proton number density, \(V_A\) is the ambipolar diffusion velocity and \(F_C\) is the conductive heat flux. The right-hand side contains the radiative energy losses per unit volume and time

\[
q_R = \int(\eta_\nu - \chi_\nu l_\nu)d\omega d\nu
\]

where \(\eta_\nu\), \(\chi_\nu\) and \(l_\nu\) are the emissivity, the absorption coefficient, and the radiation intensity, respectively, at frequency \(\nu\), and \(d\omega\) is the solid angle element.

We define the total heat flux, \(F_H\), as:

\[
F_H = U(5/2p - E_H n_1) - (5/2kT + E_H)n_p n_1/(n_p + n_1)V_A + F_C.
\]

The first term corresponds to the thermal energy carried by mass motions, the second term contains the thermal energy carried by electron enthalpy flow and ambipolar diffusion and the third term is the conductive heat flux.

In this work we assume no mass velocity \((U = 0)\).

\[
V_A = D_X d/ds[ln(n_p/n_1)] + D_T dlnT/ds
\]

assuming proton and atom diffusion velocities smaller than the thermal one.

We have also included the effect of ambipolar diffusion on statistical equilibrium equations for the different hydrogen levels and the ionized state.
The statistical equilibrium equation for any level \( m \) of the hydrogen atom is:

\[
d/ds[(n_m(V_m + U)] = P_{km}n_p - P_{mk}n_m + \sum_l (P_{lm}n_l - P_{ml}n_m)
\]

where \( n_m \) is the population of the given level, \( V_m \) is the diffusion velocity corresponding to this level, \( P_{ml} \) is the transition probability per unit time for transitions from level \( m \) to level \( l \), and \( k \) refers to the continuum.

The statistical equilibrium equation for protons is:

\[
d/ds[n_p(V_p + U)] = \sum_l (P_{lk}n_l - P_{kl}n_p).
\]

This system of equations is solved taking into account the coupling between various depths due to ambipolar diffusion.

The treatment of particle and radiation transport is consistent with the one proposed by Fontenla (1989). In this analysis he assumes that high-velocity nonthermal particles can be neglected in the energy balance and in the ionization, and he obtains models for the temperature structure using only first order departures from Maxwellian particle distributions. This approach has been confirmed by Mac Niece et al. (1991).

3. Results

With the improvements mentioned above and the increase in the number of levels of the hydrogen atom (5 in the new calculations) we have calculated four different models assuming different values for the pressure: 0.02, 0.05, 0.1 and 0.2 \( \text{dyn/cm}^2 \).

Fig. 1 shows one example of the strong influence of the ambipolar diffusion in the behaviour of \( s \) (distance to the center of the thread) versus the temperature \( T \) as compared with calculations ignoring ambipolar diffusion (i.e., setting \( V_A = 0 \)).

Fig. 2 shows the computed electron and hydrogen (level 1) populations compared with the corresponding values obtained from a model having the same \( T \) vs \( s \) distribution but computed without the effect of AD. This figure shows that the populations decrease less rapidly with increasing \( T \) than in the local ionization case in which AD is ignored. At \( T = 40,000 \) K the level 1 population is of an order of magnitude larger than in the local ionization case: the nonlocal ionization allows neutral hydrogen to be found at temperatures higher than allowed by local ionization.

In Fig. 3 we show \( s \) vs. \( T \) for four different pressures. As in the case without AD we find that the extension of the region where the temperature varies from 6,500 K to 100,000 K is larger when pressure diminishes.

In Fig. 4 we plot the proton velocity \( V_p \) and AD velocity \( V_A(= V_a - V_p) \), which almost coincides with the atom diffusion velocity \( V_a \). In the major part of the slab, \( V_a \) is small compared with the thermal velocity, but at higher \( T \), \( V_a \) may reach a sub-
Figure 1. Distance to the slab center vs. temperature. Full line: with AD, dotted line: without AD.

Figure 2. Electron and level 1 population vs. temperature. Full line: with AD, dotted line: without AD.

Significant fraction of the thermal value: at $T = 70,000$ K, the ambipolar velocity is $\sim 0.3$ times the thermal velocity ($v_{\text{ther}} \sim 34$ km/s, $V_A \sim 10$ km/s).

Fig. 5 shows that AD has a large effect on heat transport. In this figure the total heat flux $F_H$ is compared with the conductive heat flux $F_C$ corresponding to the kinetic thermal energy transport due to electrons, protons and atoms. The most
important effect shown in Fig. 5 is the dominant role of the ionization energy carried by AD for $T \lesssim 40,000$ K, due to the large value of the ionization energy as compared to the local thermal energy. As the figure shows, $F_H$ is more than an order of magnitude larger than $F_C$ at $T$ around 10,000 K. The $E_H$ term in the energy balance equation corresponds to the additional heat flux which arises because ionized particles in the
upper transition region diffuse inwards and recombine at lower temperature.

All these non-LTE computations were performed in the Complete Frequency Redistribution (CRD) approximation which, contrary to Partial Frequency Redistribution (PRD), overestimates line wing intensities. In order to compare with prominence observations, we computed precisely Lyman lines profiles in PRD, keeping the levels populations computed with AD. Because populations are kept the same in PRD and CRD, PRD effects appear only in the wings; for one thread, the opacity is too small and no PRD effect is evident. On the contrary, when the number of threads along the line-of-sight increases, the wing opacity increases and the frequency redistribution can play its role. In Fig. 6, we compare Lα profiles computed in PRD and in CRD for 200 threads along the line-of-sight, both with AD. The results of hydrogen lines profiles
computed for different models and numbers of threads, all with AD and PRD, will be presented in a forthcoming paper.

References