A PROMINENCE WITH TRANSITION REGION: HORIZONTAL TWO-DIMENSIONAL FILAMENT MODEL

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ABSTRACT

SOHO/SUMER observations of solar filaments in Lyman lines of hydrogen have revealed, in general, a two-peak form of the emission line profiles with peak to center ratio less than an order of magnitude. This fact strongly contradicts the results of numerical radiative transfer simulations, where profiles with strong dips and large (1.5–2 orders of magnitude) peak to center ratio are usually obtained due to the absence of incident radiation from above the filament and, as a consequence, very low atomic populations on the upper energy levels at the top of the filament. Recently it was shown (Schmieder et al. 1998) that this discrepancy can be removed by introducing a prominence-corona transition region (PCTR) to the radiative transfer models. This paper continues a set of publications (Anzer&Heinzel, 1999 and Heinzel&Anzer, 2001) devoted to the modelling of prominences as structures in MHS equilibrium. Here the prominence is represented by a horizontal 2D slab supported by a magnetic field. In our model we use a constant gas pressure and assume that the kinetic temperature profile and the PCTR extension are different in the vertical and horizontal directions due to magnetic field. In the PCTR the temperature sharply increases outwards from 8 000 K to 50 000 K on the scale of 100–600 km. To solve the radiative transfer problem we apply a 2D code based on the MALI iteration scheme and the modifed long characteristics method.

1. INTRODUCTION

The understanding of the nature of solar prominences remains a challenging problem for solar physicists. With recent high quality observations, especially in the UV band, it has become possible to work out more adequate theoretical and, in particular, numerical models for these solar structures. Anzer&Heinzel (1999) have analyzed the energy balance for a prominence in magnetohydrostatic (MHS) equilibrium. Radiative losses were taken from 1D non-LTE simulations (the “prominence on the limb” case) and temperature variations along the line of sight were specified by a semiempirical formula describing a steep temperature increment inside the PCTR — from 6 000 K to 30 000 K on the scale of several megameters. The gas pressure in this model decreased outwards from the center. Heinzel&Anzer (2001) have considered a case of a thin (1 Mm x 16 Mm) 2D vertical thread in MHS equilibrium supported by the magnetic field (the Kippenhahn-Slüler model). They have specified a temperature profile along the magnetic field by a semiempirical formula as in Anzer&Heinzel (1999), the temperature varied from 8 000 K to 50 000 K on the scale of 5 Mm. In the direction perpendicular to the magnetic field, the temperature increment was much steeper — the PCTR width here did not exceed 100 km. The pressure distribution was taken from the solution of MHS equations, and showed a

Figure 1. 2D modelling of the filament. Dashed lines schematically denote a real prominence, solid lines — 2D model, dotted lines — an orientation of the magnetic fields in the center of the structure.


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pressure decrement from the center to boundaries. Lyman profiles resulting from 2D non-LTE radiative transfer simulations showed a strong dependence on the line of sight orientation relative to the magnetic field. We should note that in this paper only the “prominence on the limb” case has been considered.

Both papers have shown an importance of Lyman lines as a diagnostic tool for PCTR structure determination. In the current paper we try to extend the above mentioned investigations to the case of a horizontally extended slab. Such a situation can take place in central parts of prominences and in top regions of cool postflare loops. And we can not restrict ourselves to isothermal models: since the upper part of the structure is not illuminated by the Sun, then at “cool” temperatures around 8,000 K almost all hydrogen atoms remain in the ground state, which leads to large opacities and rather small source functions in Lyman line centers. As a consequence, central intensities of Lyman line profiles become highly depressed, and the peak to center ratio become larger than factor of ten. Schmieder et al. (1998) have shown that taking into account a PCTR can rise the central intensities significantly. A sharp temperature increment in the PCTR (more than 40,000 K on the scale of 100–600 km) provides a necessary rise of the source functions to get simulated profiles close to those which are observed. In the present study we use a computer code developed for solving 2D multilevel non-LTE radiative transfer problems in solar prominences. Applying a 2D approach makes it possible to study the same structure in two “views” simultaneously: as a prominence on the limb and as a filament on the disk. These two “views” generally correspond to different orientations of magnetic field in respect to the line of sight.

We consider a prominence model with uniform gas pressure (isobaric case) and the temperature varying from the center of the structure outwards (a prominence plus PCTR). As a result we have got hydrogen spectral line profiles for “prominences on the limb” and “filaments on the disk”. For both cases we analyze the center to edge variations of these profiles.

2. HORIZONTAL 2D ISOBARIC SLAB WITH PCTR TEMPERATURE GRADIENT

In the frame of our model a prominence is represented by a 2D horizontal slab (see fig. 1). The X axis is directed along the slab, the Z axis goes vertically — along the solar radius, and the Y axis completes a right-handed orthogonal coordinate system. If we look at the slab along the Z axis, we see a “filament on the disk”, and if we look at it along the Y axis, we see a “prominence on the limb”.

We have assumed the following dimensions of the slab: length $\Delta_x = \infty$, width $\Delta_y = 3$ Mm, height $\Delta_z = 45$ Mm, and we have put the distance from solar surface to the bottom of the slab equal to 5 Mm.

![Figure 2. Structure of the prominence-corona transition region and grid points distribution in Y and Z directions.](image)

We assume that the slab is supported by a dipped magnetic field having a configuration as shown on fig. 1. Hence studying a model as a “prominence on the limb”, we look approximately along the field lines, and in the “filament on the disk” case — perpendicularly to them. For the geometry considered here, i.e. a 2D slab which has a finite vertical extension, no MHS equilibrium solution has been found so far. For this reason we consider only an isobaric slab with $P = 0.1$ dyn/cm². This type of configuration is the limit of strong magnetic fields. Moreover it requires a coronal pressure of the same value. For these reasons one has to be aware that our present model will only be a very crude approximation to any realistic prominence.

At the same time we can define a semiempirical temperature distribution, reflecting the anisotropy of plasma properties (in particular, the thermal conductivity) in the presence of magnetic fields. Similarly to Anzer & Heinzel (1999) and Heinzel & Anzer (2001) we have adopted that the temperature depends on the coordinates in the following way (fig. 2):

$$T(z, y) = T_c(z) + (T_{tr} - T_c(z)) \left(\frac{y}{\Delta_y} - 1\right)^\gamma, \quad y \in [0, \Delta_y]$$

where

$$T_c(z) = \begin{cases} T_{tr} + (T_{cen} - T_{tr}) z/\delta, & z \in [0, \delta], \\ T_{cen}, & z \in [\delta, \Delta_z - \delta], \\ T_{tr} + (T_{cen} - T_{tr}) (\Delta_z - z)/\delta, & z \in (\Delta_z - \delta, \Delta_z]. \\ \end{cases}$$

In our simulations we used the values: $T_{cen} = 8000$ K, $T_{tr} = 50000$ K, $\gamma = 10$, $\delta = 100$ km. In the direction perpendicular to magnetic field the thermal conductivity is very low, and the temperature gradient is rather large, in the other direction the temperature increment is smoother.

Due to the large temperature gradient it is impossible to get reasonable results using a standard logarithmic mesh, grid points should be fitted to the temperature distribution to get a smooth optical depth increment from point to point from the boundary inwards of the structure (fig. 2).
Figure 3. Simulated line profiles of \( \text{L}\alpha \), \( \text{L}\beta \) and \( \text{L}\epsilon \) lines. Bold lines are at the center of the filament, thin lines are near its edge. Solid lines correspond to the model with \( \text{PCTR} \), dashed lines — to the model without \( \text{PCTR} \).

To calculate opacities for spectral lines, we need to know one more plasma parameter — turbulent velocity \( V_{\text{turb}} \). As in previous papers, we assume it to be equal to 5 km/s.

3. 2D MULTILEVEL RADIATIVE TRANSFER

We assume that both hydrogen and helium contribute to the total gas pressure, but only hydrogen supplies electrons to the plasma: \( N_e = N_{\text{HII}} \). If \( Y \) is the helium abundance with respect to hydrogen, then the total gas pressure is related to the kinetic temperature by the expression:

\[
P = [(N_{\text{HI}} + N_{\text{HII}})(1 + Y) + N_e] kT
\]

We solve the radiative transfer problem only for hydrogen. Similarly to Schmieder et al. (1998) we used 12-level plus continuum atomic model. All bound-bound radiative transitions among the lower 5 levels, all Lyman lines and the Lyman continuum were treated in detail, by solving the radiative transfer equation. Radiation in other transitions is optically thin in the prominence plasma and we assume it to be equal to the diluted solar radiation at the given height above the Sun.

To solve the non-LTE problem we used a MALI iterative method (Rybicky & Hummer, 1991, 1992) with an additional linearization procedure for particle densities to get consistent hydrogen ionization (Heinzel, 1995). Effects of partial frequency redistribution in \( \text{L}\alpha \) and \( \text{L}\beta \) lines were taken into account.

In the frame of the MALI method, in each iteration it is necessary to get a 2D formal solution of the radiative transfer equation (RTE). To do that we used a modified long characteristics method proposed by Gorskov (1996): for a given direction in the YZ plane a set of long characteristics covering the whole 2D crosssection is designed (to get the so called "RTE grid" for this direction). After that we interpolate to every characteristics the necessary values (kinetic temperature, turbulent velocity, atomic level populations etc.) from the "basic" grid, perform the formal solution along the characteristics according to the Rybicky&Hummer (1991, 1992) technique. The last step is a backward interpolation of radiative integrals (to be substituted to the MALI equations) to the "basic" grid. The "RTE grid" points are chosen with the aim to provide a 1D interpolation in the direction parallel to the nearest boundary — then physical parameters vary most smoothly from point to point.

4. RESULTS

As a result of our simulations we have obtained spectral profiles of 17 hydrogen lines (including Lα—L11, Hα, Hβ, Pα etc.) and the Lyman continuum for every boundary point and both "views" of the structure — "prominence on the limb" and "filament on the disk". Due to the lack of space we present here only the Lα, Lβ and Lε profiles for both "views", and only for a few points across the structure (see fig. 3). It is clearly seen that the including of a PCTR to prominence spectra simulations dramatically increases the central intensity of Lyman lines for a "filament on the disk" — up to 1.5 orders of magnitude in our case — and does not affect significantly the wings of the line almost everywhere with the exception of those regions where one integrates along the PCTR itself, where the higher intensities are due to the higher source functions forming in the regions with higher temperature. The effect of the PCTR is also quite significant for the "prominence on the limb" profiles — the central intensities of Lyman lines rise by up to 50 % in the center of the structure, while the wings are not affected by the PCTR. Near the boundary the line intensities drop down due to the lack of background radiation and a relatively small amount of emitting atoms along the line of sight — PCTR plasma at temperatures higher than 20,000 K is almost completely ionized and optically thin for hydrogen radiation.

5. CONCLUSIONS

We can conclude that the PCTR highly affects the spectral profiles of hydrogen lines, in agreement with previous resulstes of Schmieder et al. (1998). The effect depends on the total optical depth in the line center. Therefore it is possible to use Lyman lines as an indicator of the PCTR temperature distribution. As a next step it would be interesting to try to fit the line profiles of the Lyman series which were observed by SUMER using 2D models discribed here.

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