PROMINENCE FINE STRUCTURES IN A MAGNETIC EQUILIBRIUM:
A GRID OF TWO-DIMENSIONAL MODELS

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ABSTRACT

We construct a grid of 2D vertical-thread models for prominence fine structures which are in magnetohydrostatic (MHS) equilibrium. Such thread models have been described in a previous paper by Heinzel & Anzer (2001). Our grid consists of 18 models which cover a range of central column masses, magnetic-field intensities and two parameters characterising the 2D temperature structure of the thread. Since different Lyman lines and their parts (line center, peak, wings) are formed at different places within the thread, the Lyman series may serve as a good diagnostic tool for thermodynamic conditions varying from central cool parts to a prominence-corona transition region. We demonstrate this behaviour for various lines, showing their synthetic profiles as seen from two perpendicular directions along and across the magnetic field lines, respectively, and displaying the respective contribution functions.

1. INTRODUCTION

The spectral observations of hydrogen Lyman lines and continuum obtained by the SUMER UV-spectrograph on SOHO (Solar and Heliospheric Observatory) represent an important constraint on prominence modelling. Various examples of such data and their analysis can be found in Schmieder et al. (1998, 1999, 2003) and Heinzel et al. (2001); see also a review of SOHO prominence observations by Patsourakos & Vial (2002). The formation depths of these optically-thick lines span the whole prominence structure and thus the line profiles of the Lyman series can provide us with a reliable diagnostics of prominence/filament thermodynamic conditions. In order to interpret properly the Lyman-line profiles, one has to perform rather complex non-LTE radiative transfer computations using sophisticated models.

2. 2D MODELS OF QUIESCENT PROMINENCES

Three important aspects play a role in the spectral-line formation: the pressure structure, the temperature variation in the prominence-corona transition region (PCTR) and the depth variations of the line source functions. The pressure structure is described by 2D MHS equilibria (Heinzel & Anzer 2001). The temperature profile is in principle determined by the energy balance, but here we model it by an ad hoc spatial variation given by formula

\[ T(m, y) = T_{cen}(y) + (T_{tr} - T_{cen}(y)) \left( 1 - \frac{m}{M(y)} \right)^{\gamma_1} \left( 1 - \frac{m}{M(y)} \right)^{\gamma_1} \]

where \( T_{tr} \) represents the temperature at the boundary and the exponent \( \gamma_1 \) has to be chosen properly. The temperature at \( x=0 \), \( T_{cen}(y) \), is given by

\[ T_{cen}(y) = T_{tr} - (T_{tr} - T_0) \left( 1 - \frac{y}{\delta} \right)^{\gamma_2} \]

for \( |y| \leq \delta \).

\( T_0 \) is the (minimum) central temperature, \( 2\delta \) represents the width of the thread in \( y \)-direction (perpendicular to the field lines) and the exponent \( \gamma_2 \) is again a free parameter.

3. GRID OF MODELS

The shape of synthetic spectral-line profiles obtained by radiative transfer modelling depends on the set of input parameters which describe the MHS equilibrium, the form of temperature structure, and on the incident radiation. The set of input MHS-parameters fully determines the shape of the magnetic dips and will influence the shape of the calculated synthetic profiles. The full description of all input MHS-parameters has been presented in Heinzel & Anzer (2001) and Heinzel et al. (2005).

In order to describe the dependence of the synthetic profiles on given input parameters we have constructed a grid of 18 prominence models. Within this grid of models we
Table 1. Parameters for the model grid

<table>
<thead>
<tr>
<th>Models of series A</th>
<th>Models of series B</th>
<th>Models of series C</th>
<th>( M_0 ) [g cm(^{-2})]</th>
<th>( B_\alpha(0) ) [Gauss]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_1 = 5 )</td>
<td>( \gamma_1 = 10 )</td>
<td>( \gamma_1 = 10 )</td>
<td>( \gamma_2 = 30 )</td>
<td>( \gamma_2 = 30 )</td>
</tr>
<tr>
<td>( \gamma_2 = 30 )</td>
<td>( \gamma_2 = 60 )</td>
<td>( \gamma_2 = 30 )</td>
<td>( \gamma_2 = 30 )</td>
<td>( \gamma_2 = 30 )</td>
</tr>
<tr>
<td>( A_1 )</td>
<td>( B_1 )</td>
<td>( C_1 )</td>
<td>( 2.1 \times 10^{-4} )</td>
<td>8.4</td>
</tr>
<tr>
<td>( A_2 )</td>
<td>( B_2 )</td>
<td>( C_2 )</td>
<td>( 5.1 \times 10^{-5} )</td>
<td>4</td>
</tr>
<tr>
<td>( A_3 )</td>
<td>( B_3 )</td>
<td>( C_3 )</td>
<td>( 2.1 \times 10^{-5} )</td>
<td>2</td>
</tr>
<tr>
<td>( A_{3,1} )</td>
<td>( B_{3,1} )</td>
<td>( C_{3,1} )</td>
<td>( 2.1 \times 10^{-5} )</td>
<td>10</td>
</tr>
<tr>
<td>( A_4 )</td>
<td>( B_4 )</td>
<td>( C_4 )</td>
<td>( 5.1 \times 10^{-6} )</td>
<td>1</td>
</tr>
<tr>
<td>( A_{4,1} )</td>
<td>( B_{4,1} )</td>
<td>( C_{4,1} )</td>
<td>( 5.1 \times 10^{-6} )</td>
<td>5</td>
</tr>
</tbody>
</table>

varied \( M_0 \), \( B_\alpha(0) \) and the exponents \( \gamma_1 \) and \( \gamma_2 \), where \( M_0 \) is the maximum column density and \( B_\alpha(0) \) is horizontal field in the middle of the thread.

The model grid consists of three series with 6 models for each of them. The series differ only in the value of one of the \( \gamma \)-parameters. The models in each series have different values of \( M_0 \) and \( B_\alpha(0) \). The full list of our model grid is summarised in Tab. 1. Geometrically all these models represent structures with a width of 1000 km and their lengths vary between 2000 km and 25000 km. The length of models is determined mainly by the magnetic field strength and the column mass, and to some extent also by the temperature structure. Variations of the input parameters for our 18 models have an essential effect on the magnetic field structure (dip) and therefore lead to different extensions in \( x \)-direction.

4. SYNTHETIC PROFILES

In this section we discuss the dependence of our synthetic profiles on the values of the input parameters defining individual models, as well as their variation with the viewing direction. All line-profile plots are also available at http://www.asu.cas.cz/~radtrans.

4.1. Dependence on the field orientation

As was shown in Heinzel et al. (2001), the computed Lyman-line profiles of prominences strongly depend on the viewing angle with respect to the magnetic-field orientation.

In Fig. 1 we show L\( \beta \), L7 and L6 line profiles and the intensity plots. Full lines result from averaging along the dip thickness \( 2\theta \) (i.e. over \( y \)), dashed lines represent averaging along the whole dip length (i.e. in the \( x \)-direction). The intensity plots show the variation of the line intensity as a function of \( x \) and wavelength from the front (first column) and from the rear (second column). Each profile there represents a mean profile averaged locally over 1000 km in \( x \)-direction.

The field orientation has a two-fold effect on the Lyman-line shapes. First, the density distribution along the field lines is given by the MHS equations, while across the field lines the column mass \( M(y) \) can vary in a rather arbitrary way because the individual flux tubes are magnetically separated. Second, along the field lines the temperature variation is supposed to be relatively smooth because of efficient heat conduction. On the other hand, the heat conduction across the field lines is strongly inhibited and thus the temperature profile exhibits a rather steep gradient at the boundaries.

From our grid of models we conclude that the Lo profiles are rather similar when one looks along the \( x \)-axis and when one looks in \( y \)-direction. But for all higher lines we see that in general the line profiles are much more reversed when we look along the \( y \)-axis (i.e. across the field lines). The \( x \)-variation of the line intensity shows that in the center of the structure (at \( x=0 \)) the reversal is not very pronounced, but it strongly increases outside the central parts. Finally, approaching the boundaries where \( p \rightarrow p_0 \), the profiles become unreversed with a central emission peak.

4.2. Dependence on the shape of temperature structure

The shape of the temperature structure is fully described by the exponents \( \gamma_1 \) and \( \gamma_2 \). For the discussion of effects of the temperature structure on the line profiles it is useful to compare two models which differ only in one of these parameters.

4.2.1. Effect of the exponent \( \gamma_1 \)

Here we compare models \( A_1 \) and \( C_1 \) which differ in \( \gamma_1 \) (\( \gamma_1 = 5 \) for \( A_1 \) and \( \gamma_1 = 10 \) for \( C_1 \)). We demonstrate the effect of changes of the exponent \( \gamma_1 \) on L\( \beta \).

The center of this spectral line for both directions of view forms at the boundary of the prominence structure (Fig. 2), in areas with a high temperature rising up to the boundary value of 50000 K where \( p \rightarrow p_0 \). Model \( A_1 \) gives the higher value of a specific intensity in the line center and peak (more than 40%) compared to model \( C_1 \).

This is due to a higher temperature in the region of the center and peak formation (Fig. 2). The temperature is higher because we keep the boundary temperature fixed and have a lower temperature gradient close to the boundary for \( A_1 \), given by the lower value of the parameter \( \gamma_1 \).

The wings of spectral lines are mostly optically thin and originate in the center of the thread, the place with a low temperature, high density and negligible influence of the parameter \( \gamma_1 \).

The detailed description of the line profiles dependencies on all parameters is given in Heinzel et al. (2005).

5. DISCUSSION AND CONCLUSIONS

We discuss (Heinzel et al. 2005) how the magnetic field configuration of a vertical prominence thread can influ-
ence the structure of the prominence–corona transition region. As we show, depending on this structure one obtains different line profiles for the series of Lyman lines, namely when looking, respectively, along and across the magnetic-field lines. Studying these lines can give us important information on the physical conditions in the prominence threads. In future work we intend to apply this modelling to sets of Lyman-line profiles observed in prominences by SOHO/SUMER. By searching for the best fit simultaneously to all observed Lyman profiles one should be able to determine in detail the physical structure of prominence threads. However, this may require a more complex modelling based on multi-thread configurations - several threads seen along the line-of-sight which passes across the magnetic-field lines or even 3D models.

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REFERENCES

Figure 2. Line profiles and contribution functions for Lβ of models A₁ (top) and C₁ (bottom). The upper pairs of contribution plots of each model are for the central frequency, the middle pairs are for the peak frequency and the lower ones represent contributions in the line wings. On the left-hand side the viewing is in the direction along the x-axis, on the right-hand side in the y-direction. Isothermal contours are plotted in steps of 10000 K. x - y dimensions are in cm.