NLTE ANALYSIS OF SUMER FILAMENT OBSERVATIONS ON SOHO *

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ABSTRACT

We describe the first observations of hydrogen Lyman lines (Lα, Lβ, L6, L7) in a filament made by the SUMER spectrograph onboard the SOHO satellite. The data have been obtained in the raster mode and we present here a set of typical line profiles which exhibit a rather strong central reversal. All lines have been calibrated to absolute intensities. We used the multilevel NLTE code based on the MALI technique in order to evaluate theoretical line profiles of the four Lyman lines studied. As a result we have found that the line cores of all these Lyman lines are good indicators of the temperature structure of the filament and, moreover, the line wings are sensitive to the gas pressure. In particular, it becomes clear that simple isothermal models cannot explain the line-core intensities and, therefore, one has to consider more realistic models with the prominence-corona transition region (PCTR). A steep temperature increase in the PCTR seems to be consistent with the observed enhanced intensities in the line cores of the four Lyman lines.

Key words: SOHO-SUMER, filaments, NLTE models

1. INTRODUCTION

The diagnostic of the prominence (filament) plasma has relied on different techniques among which the use of optically thick lines offers the possibility of scanning the different regions along the line-of-sight. However, the price for this advantage is the complexity of the diagnostic (which implies NLTE radiative transfer) and also a complex pattern of parameters intervening in the formation of the lines. OSO-8 and SMM observations in Lyman lines of hydrogen (along with Mg II and Ca II) have been used to derive temperature, density, pressure and ionization degree from heavy NLTE modelling (see e.g. Gouttebroze et al. 1993 and Heinzel et al. 1994). Such a modelling allowed to predict observables in Lα and Lβ lines (the only ones observed at that time) along with Balmer lines. With the advent of SUMER, we now have the capability to observe higher Lyman lines up to the Lyman edge, with a unique spectral resolution (Wilm et al. 1995). The upper levels of these lines are populated by numerous processes which involve the Lyman transitions themselves but also subordinate lines and continua. Their broadening is also more and more sensitive to Stark effect and it is difficult to predict which thermodynamic parameters are critical in the formation of these lines. Only detailed NLTE computations can answer this question. We present here preliminary results concerning the first detailed observations and NLTE computations of these lines in a filament (see also Schmieder et al. 1997).

2. FILAMENT OBSERVATIONS WITH SUMER

On September 21, 1996, a filament close to an enhanced network was observed with SUMER and CDS instruments onboard the SOHO satellite. The target of SUMER was a part of the north-south filament (S 6-12, E 5). For a SUMER instrument description we refer to Wilhelm et al. (1995). Four Lyman lines - Lα, Lβ, L6 and L7 - were detected by SUMER using the raster mode. Rastering was performed with the slit 120 arcsec long (1 arcsec wide) over the region of 150 arcsec, with a raster step of 3 arcsec. An example of a raster in the Lβ line is shown in Fig. 1. The exposure time was 60 sec. In the wavelength range 920 to 950 Å, seven windows of 50 x 120 pixels each were displayed on the detector A, with one window on the bare part (949.7 Å). Seven prominent emission lines have been well detected: Lα (949.74 Å), Lβ (937.80 Å), L6 (930.75 Å) and L7 (926.23 Å), together with the lines of S VI (944.54 and 933.38 Å) and of N IV at 923.22 Å.

2.1. Data Processing

The observations have been corrected with a flat-field image obtained on 24 September 1996. The curvature of the lines depends on their position on the detector and it is necessary to make corrections for

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an 'inverse-cushion' distortion of the detector. The spectra were thus destretched by using the SUMER analysis software procedure destretch.pro provided by T. Moran.

Wavelength calibration was done by using the Lyman lines on the quiet Sun nearby the filament. The profiles were fitted by gaussians. We have derived the mean dispersion to be 0.04445 Å/pixel. We have found that the measured wavelengths are shifted relative to the standard wavelengths by an amount corresponding to less than 0.015 Å which corresponds to about one third of the pixel (4 km/sec).

The intensity calibration was performed with the procedure of Wilhelm et al. (1997), called radiometry-A.pro. The resulting profiles are displayed in Fig. 2 in units of W/sr/m²/Å. The full profiles with strong self-reversal correspond to the filament and they have been obtained by summing 10 pixels along the slit. The intensities corresponding to the filament environment (dashed lines, average over 5 spectra) are consistent with those given by Wilhelm (1997) for the quiet Sun, but we have found a small increase by a factor of about 1.3 at the peak values - we interpret this as due to the presence of a network boundary in the field used for averaging. For a comparison with theoretical profiles we have converted the absolute intensities into units of erg/sec/cm²/sr/Hz.

3. THE BEHAVIOUR OF HIGHER LYMAN LINES IN THE FILAMENT

From Figures 1 and 2 we can draw the following conclusions. All four lines exhibit a rather strong central reversal, which is not present in the background spectrum (except of a weak feature in L6). Peaks are asymmetrical with higher red peaks. On the contrary, we do not observe any significant shift of filament lines with respect to the background emission. Line intensities are somewhat smaller as compared to the background, because of a strong absorption in the filament. Spatial variations of the Lyman lines (intensities, widths, asymmetries) in the filament can be studied by using the raster data (Fig. 1).
4. NLTE MODELS OF THE FILAMENT

In this exploratory paper we try, for the first time, to analyze higher Lyman lines in the filament and to reproduce quantitatively the observed line intensities with the existing models. To do this, we start here with a standard one-dimensional (1D) filament model represented by a horizontal slab having a finite vertical thickness (see e.g. Mein et al. 1996). With this simple geometrical model we concentrate mainly on the detailed atomic physics, realistic incident radiation and filament temperature structure.

4.1. Atomic Model

We use a twelve-levels plus continuum hydrogen model atom which gives a reasonable representation of the four studied lines. The line wavelengths and oscillator strengths are taken from the NBS tables and the collisional excitation and ionization rates are computed according to Gouttebroze (1997). For higher members of the Lyman series, the Stark broadening plays a role and we have estimated the proper Stark widths using the same schematic approach as in Gouttebroze et al. (1978). In Table 1 we summarize the values of natural line width $\Gamma_N$, Stark width $\Gamma_S$ and multilevel PRD-parameter $\lambda$. The latter parameter shows the role of the partial-frequency redistribution (PRD) for a given line transition (Heinzel et al. 1987). PRD is important when $\lambda$ is close to unity, which is mainly the case of L$\alpha$ and L$\beta$ lines. For L$\delta$ and higher lines, one can neglect PRD. From Table 1 we also see that the Stark broadening starts to dominate the natural one for lines higher than L$\delta$ (electron density $2 \times 10^{10}$ cm$^{-3}$ was used to compute $\Gamma_S$ and $\lambda$).

<table>
<thead>
<tr>
<th>Line</th>
<th>$\Gamma_N$</th>
<th>$\Gamma_S$</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>L$\alpha$</td>
<td>4.7E8</td>
<td>4.8E5</td>
<td>0.999</td>
</tr>
<tr>
<td>L$\beta$</td>
<td>1.0E8</td>
<td>3.6E6</td>
<td>0.540</td>
</tr>
<tr>
<td>L$\gamma$</td>
<td>3.0E7</td>
<td>1.2E7</td>
<td>0.304</td>
</tr>
<tr>
<td>L$\delta$</td>
<td>1.2E7</td>
<td>1.8E7</td>
<td>0.138</td>
</tr>
<tr>
<td>L$\epsilon$</td>
<td>5.2E6</td>
<td>3.8E7</td>
<td>0.038</td>
</tr>
<tr>
<td>L$\delta$</td>
<td>2.6E6</td>
<td>5.1E7</td>
<td>0.014</td>
</tr>
<tr>
<td>L$\gamma$</td>
<td>1.4E6</td>
<td>8.7E7</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Figure 3. Theoretical NLTE half profiles (full lines) computed with an isothermal model having $T = 7000$ K. They are compared to the observed profiles (dashed lines) which have been averaged over the red and blue parts of full profiles.
Figure 4. Theoretical NLTE half profiles (full lines) computed with an isothermal filament core (T=7000 K) and a narrow PCTR rising to T=14000 K. A reasonable fit is obtained, particularly for the Le line.
4.2. MALI Method

To solve the multilevel NLTE transfer problem in a 1D slab, we use the MALI method described in Heinzel (1995). PRD in Lo and L3 is implemented according to Paletou (1995). The boundary conditions for horizontal slabs are discussed in Mein et al. (1996). Our present study is the first one where higher Lyman lines are computed in detail - all previous prominence models used either few bound levels only or the detailed radiative balance in higher Lyman transitions (Milkey and Heasley 1978; Gouttebroze et al. 1993). Detailed transfer treatment in higher Lyman lines (considered as explicit transitions) is of course necessary in order to reproduce the observed line profiles and calibrated intensities and for this the Multilevel Accelerated Lambda Iteration (MALI) techniques are well suited. However, we need to specify carefully the incident radiations.

4.3. Incident Radiation Fields

For the multilevel hydrogen atom we use here the same incident radiation fields as in Gouttebroze et al. (1993) who treated up to 30 levels. For the four Lyman lines analyzed here we use the mean disk profiles shown in Fig. 2 (neglecting any variations over the disk) and for lines higher than L-7 we use the profile of L-7 scaled by the ratio of the central-peak intensities as measured by SUMER (Wilhelm 1997). For the photoionization in subordinate continua we use the rates summarized by Rudawy and Heinzel (1993).

Specifically for filaments seen against the solar disk, one also has to know the specific intensity of radiation emerging from the disk in the direction to the observer - this is used in the formal solution of the transfer equation as the so-called background profile.

5. TEMPERATURE STRUCTURE

As an initial attempt to model these Lyman lines, we used the same isobaric and isothermal models as in Gouttebroze et al. (1993). However, it became immediately clear that such simple models cannot reproduce the observed line profiles, particularly in the line center. The situation for $T = 7000 \text{ K}$, gas pressure $p = 0.1 \text{ dyn cm}^{-2}$ and a filament vertical extension of 20000 km is shown in Fig. 3.

The profile fitting can be largely improved if one adds a prominence-corona transition region (PCTR). By trial and error, we have tried to determine the temperature gradient in PCTR in order to better fit the Lyman lines cores. The result is shown in Fig. 4, where a rather good agreement is achieved for Lr, while the other three lines are not so well reproduced (although their core intensities have been substantially risen). Note that several small peaks appearing on the theoretical line profiles of Fig. 4 are due to a schematic representation of the PCTR temperature gradient. PCTR temperature increased up to 14000 K on scale of few hundreds km.

6. FURTHER PROSPECTS

Our NLTE simulations have indicated the sensitivity of Lyman lines cores to the temperature structure in PCTR and the sensitivity of the line wings to gas pressure (at least for higher pressures which lead to optically-thick wings). Therefore, we conclude that these hydrogen lines are diagnostically important and should be used for analyzing the temperature and density structure inside the filaments. New data have been recently collected in these lines (MEDOC campaign during May-June 1997) and they will be analyzed. We shall also address the questions of the filament fine structure and consider 2D models. However, some preliminary 2D computations (Gorskov 1997) show that 2D transfer effects cannot produce the enhanced line-core intensities and thus the PCTR temperature gradient seems to be the most appropriate explanation.

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