NON-LTE MODELLING OF THE EUV FILAMENT BASED ON SOHO/SUMER
OBSERVATIONS OF THE HYDROGEN LYMAN LINES

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ABSTRACT

The plasma properties of an EUV filament observed by SoHO on 15 October 1999 were studied using non-LTE modelling of hydrogen Lyman line profiles. Modelling of the part of the EUV filament visible in the Hα line gave us similar results to those published elsewhere: temperature around 10000 K, gas pressure \( \sim 0.1 \text{ dyn cm}^{-2} \) and optical thickness much larger than unity. In EUV extension the temperatures were much higher, gas pressure lower comparable to coronal values and optical thickness \( \sim 10^{-2} \). This means that reduction of intensity of coronal lines in the EUV extension can be only due to the volume-blocking mechanism, not due to absorption. But for transition-region lines with wavelength below 912 Å a darkening could be explained only by absorption. Therefore we suggest sort of hybrid model composed of high-lying extended optically thin structures and of low-lying optically thick structures.

1. INTRODUCTION

It has already been presented (see e.g. Heintel et al. (2001); Schmieder et al. (2003); Schmieder et al. (2004)) that filaments are more extended when observed in EUV spectral lines emitted from corona or transition region (hereafter TR) than their counterparts observed in the Hα line. Those extended dark structures observed in EUV are called EUV filaments. The intensity reduction in comparison to EUV-filament vicinity can be explained by two plausible mechanisms: absorption by resonance continuum and volume blocking.

The first mechanism concerns the absorption by resonance continua of neutral hydrogen and of neutral and ionized helium (e.g. Anzer & Heintel, 2005). EUV radiation emitted from TR and corona beneath the EUV filament with wavelength lower then the head of hydrogen Lyman continuum (912 Å) is absorbed by EUV filament. The darkest parts of the EUV filament are clouds of cool and optically thick plasma. Therefore these structures can produce observable contrast also in the Hα line (Hα filaments). Other parts of the EUV filament are optically thin in the Hα line but they could be optically thick for EUV lines with wavelengths lower than 912 Å. These parts are called EUV extensions and are visible only in the EUV spectral range. The second mechanism – volume blocking can influence mainly intensities of coronal EUV lines. This mechanism is based on the fact that hot coronal lines cannot be emitted from volume of the EUV filament occupied by relatively cool plasma. This mechanism is independent of optical thickness of the EUV filament and of the wavelength. The geometrical thickness of the EUV filament is the only parameter determining contribution of this mechanism to intensity reduction. Both absorption and volume blocking can contribute together to the intensity reduction in EUV filaments (Schwartz et al., 2004). If we want to know relative contributions of absorption and volume blocking to intensity reduction we have to know the optical thickness. In our previous paper (Schwartz et al., 2004) we took the optical thickness as a free parameter. In this paper we reproduce profiles of hydrogen Lyman lines observed in the EUV filament with synthetic profiles computed using the non-LTE model. This model computes also the optical thickness which makes possible to estimate the ratio of contributions of absorption and volume blocking to intensity reduction and also to adjust heights of the EUV extension estimated in our previous paper.

2. OBSERVATIONS

The observations with CDS (Coronal Diagnostic Spectrometer) (Harrison et al., 1995) on-board of SoHO (Solar and Heliospheric Observatory) were made on 15 October 1999 between 10:01 and 10:52 UT. Carrington heliographic coordinates of the raster center are N 37.6, E 19.3 (−253.8 arcsec, 512.8 arcsec in SoHO coordinate system) and dimensions of rasters are 244 arcsec × 240 arcsec. Among the observed EUV lines, we chose for our study two coronal lines Mg \text{x} 624.94 Å, Si \text{xii} 520.60 Å and one TR line \text{O \, v} 629.73 Å. A raster in the Mg \text{x} coronal line
is shown in Fig. 1. More details about these CDS observations can be found in Schwartz et al. (2004).

Spectra of hydrogen Lyman lines Lβ, Lδ, Lε, L6 and L7 used for our modelling were obtained by SoHO/SUMER (Solar Ultraviolet Measurements of Emitted Radiation) (Wilhelm et al., 1995) approximately at the same time (10:42 – 10:57 UT) as the observations of CDS. The slit with dimensions 1 arcsec × 120 arcsec was positioned across the EUV filament. The spectra are shown in Fig. 2. In these spectra, several sections are marked: Three sets of EUV-extension line profiles were taken averaged along the sections on SUMER slit marked as EUV-extension section I – III. One set of line profiles averaged along the section marked Hα filament was used for modelling the part of the filament visible in Hα. Line profiles averaged along the section quiet chromosphere were used for reconstruction of the background irradiation of the EUV filament. Position of the SUMER slit in raster of CDS observations was estimated using co-alignment between these two instruments. This was made in two steps: First the positions of a dark feature of the EUV filament in the CDS raster in the He I 584.33 Å and in the SUMER raster in the Lδ line were compared. Both rasters were obtained at approximately same time (from 11:24 to 12:07 UT) and also horizontal dimension of pixel in both raster is almost the same (∼1.5 arcsec). Therefore comparison could be performed without any resampling and transformations and approximate horizontal position of the SUMER slit in CDS raster was estimated. In the second step the SUMER observations of the line O vi 1031.9 Å and CDS observations of the line O V 629.7 Å were co-aligned. The O vi line was observed by SUMER together with Lβ (both lines lie in the same spectral window). The O V line was observed during the same CDS observations as the Mg X line (shown in Fig. 1). For correct position of the SUMER slit the distributions of intensities of both oxygen lines should correlate well in the quiet-Sun areas as it is shown in Fig. 3. Between two quiet-Sun sections the slit crosses the EUV filament where the O V radiation is absorbed by filament plasma. After this co-alignment the position of the SUMER slit was estimated. Center of the slit has coordinates: X=−254±2 arcsec Y=513±2 arcsec in SoHO coordinate system or X=122±2 arcsec Y=120±2 arcsec in the CDS raster shown in Fig. 1. In this figure only mean position of the SUMER slit is shown.

3. NON-LTE MODEL OF A FILAMENT

The filament is approximated by a horizontal one-dimensional slab (1D slab). 1D slab means the slab infinite in both horizontal directions. The only finite dimension is the vertical width of the slab which represents the geometrical thickness of a filament. Temperature is changing only with height above the solar surface. Therefore the plasma properties and the radiation field are the same everywhere along each horizontal layer of the slab. We assume that:

- 1D slab is irradiated only from the solar atmosphere beneath
- there are two analogous prominence-corona transition regions (PCTR); one on the top, another at the bottom of the slab
- temperature decreases from both PCTRs to the slab interior symmetrically
temperature decrease is steep only in PCTR\textsubscript{s}, in the slab interior the temperature distribution is rather flat.

- gas pressure is constant in the whole slab
- turbulent velocity is not larger than 10 km s\textsuperscript{-1}

For the solution of equation of radiative transfer and of equations of statistical equilibrium we used codes of Heinzl et al. (1997). MALI (Multilevel Accelerated Lambda Iterations) method (Heinzl, 1995; Pale
tou, 1995) with 12-level model of hydrogen atom is used for non-LTE solution of radiative transfer in these codes. Disk averaged profiles of hydrogen Lyman lines of Warren et al. (1998) were used for construction of the radiation field used in computations of the source functions across the 1D slab.

Line profiles of the background irradiation were reconstructed. Optically thin wings of these profiles were obtained using multiplication of average line profiles from the section quiet chromosphere by constants properly adjusted so that profiles of background irradiation fitted the filament profiles in the wings. Optically thick cores of the profiles were reconstructed using the quiet-Sun profiles of Warren et al. (1998).

4. RESULTS

Geometrical thickness \(D\) and heights \(h_\text{fb}\) of the bottom border of the 1D slab for EUV-extension sections I – III were computed using the spectroscopic model of Heinzl et al. (2003) and CDS observations of the lines Mg\textsc{x} 624.94 Å and Si\textsc{xii} 520.60 Å. For details about these computations see Schwartz et al. (2004). First we used \(D\) and \(h_\text{fb}\) averaged through values computed for the optical thickness \(\tau_{912}\) at hydrogen Lyman continuum head ranging from 0.1 to 3. After the first non-LTE modelling approximate values of \(\tau_{912}\) were known. New values of \(D\) and \(h_\text{fb}\) were computed for these approximate values of \(\tau_{912}\) using spectroscopic model. After the second non-LTE modelling we obtained almost the same values of \(\tau_{912}\) therefore further iterations were not necessary. For H\textalpha{} filament only height \(h_\text{f}\) was 45 700 km of the top boundary of the filament was known. Therefore \(D\) was taken as a free parameter of the non-LTE model and height \(h_\text{fb}\) was computed as \(h_\text{fb} = h_\text{f} - D\).

We computed different grids of our non-LTE 1D-slab models for EUV-extension sections I – III and H\textalpha{}-filament section for many different sets of input parameters. The best models were found using the \(\chi^2\) optimisation:

\[
\chi^2_{\text{norm}} = \frac{\sum_{l=1}^{n_\text{L}} \sum_{i=1}^{n_\text{w}(l)} \left[ I_i^{\text{obs}}(\lambda_l) - I_i^{\text{syn}}(\lambda_l) \right]^2}{\sum_{l=1}^{n_\text{L}} \sum_{i=1}^{n_\text{w}(l)} \left[ \delta I_i^{\text{obs}}(\lambda_l) \right]^2 \max(I_i^{\text{obs}})}
\]

where \(I_i^{\text{obs}}(\lambda_l)\) and \(I_i^{\text{syn}}(\lambda_l)\) are intensities of the observed and computed profile of the line \(l\) at wavelength \(\lambda_l\). \(\delta I_i^{\text{obs}}(\lambda_l)\) is an error of measurement of the observed line intensity. \(\max(I_i^{\text{obs}})\) is maximal intensity of observed profile of spectral line \(l\). \(n_\text{L}\) is the number of observed spectral lines (in this work we use 5 lines) and \(n_\text{w}(l)\) is the number of wavelengths in which the profile of the line \(l\) was observed. Example of the comparison of observed profiles averaged along the EUV-extension section I with synthetic profiles computed by the best model is shown in Fig. 4.

In EUV-extension sections I and III values of \(h_\text{fb}\) and \(D\) are around 12 000 km and 39 000 km, respectively. Temperatures are rather high from 35 000 to 40 000 K, gas pressure is low ~0.1 dyn cm\textsuperscript{-2}, the plasma density around \(2 \times 10^{15}\) g cm\textsuperscript{-3} and hydrogen is almost fully ionized. Filling factor, defined as a fraction of the geometrical thickness of the slab filled with cool EUV-
-filament plasma, is lower than 0.5. PCTR s are geometrically thick — several thousands km. Optical thickness \( \tau_{\text{H}^0} \) at the hydrogen Lyman continuum head and \( \tau_{\text{H}^\alpha} \) at the center of the H\( \alpha \) line are of the order of \( 10^{-2} \) and \( 10^{-4} \), respectively. In EUV-extension section II which is close to the H\( \alpha \) filament, results are similar. But height of the filament is much lower \( h_\text{slab}=5000 \text{ km} \), temperature and ionization degree in the slab interior are 9000 K and 0.9, respectively. This temperature is close to a typical value for H\( \alpha \) filaments. Plasma density is an order of magnitude higher. Values of optical thickness \( \tau_{\text{H}^\alpha} \) are 4.6 and 0.3, respectively. EUV-filament at section H\( \alpha \) filament is rather high (39000 km) and geometrically thin (6000 km). Temperatures are around 15000 K and in the slab interior they are lower than 10000 K. Gas pressure and plasma density are an order of magnitude higher than in EUV-extension sections. Ionization degree ranges from 0.1 to 0.8. Filling factor is 0.7. There are high values of the optical thickness \( \tau_{\text{H}^\alpha} \) and \( \tau_{\text{H}^0} \), 330 and 6, respectively. As it was expected this part of the EUV-filament is visible also in the H\( \alpha \) line.

5. DISCUSSION AND CONCLUSIONS

Results of our non-LTE modelling of the H\( \alpha \) part of the filament, i.e. rather low temperatures (lower than 10000 K) and very large optical thickness, are similar to results of Schmieder et al. (2003) who made diagnostics of another filament observed in H\( \alpha \) and EUV on 5 May 2000.

In our previous paper (Schwartz et al., 2004) we assumed that high-lying EUV extension is optically thick at the hydrogen Lyman continuum. Large optical thickness \( \tau_{\text{H}^\alpha} \) was needed to explain the appearance of dark patterns in the O\( \nu \) 629.7 Å line, while O\( \nu \) 1031.9 Å located above the Lyman-continuum head was not affected by the absorption (compare plots of intensities of these two lines in the area between two quiet-Sun regions in Fig. 3). But the optical thickness \( \tau_{\text{H}^\alpha} \) obtained by present non-LTE modelling based on Lyman lines is very low. It means that the EUV extension is not optically thick at hydrogen Lyman continuum. The coronal lines like Mg\( \text{x} \) 624.94 Å, Ca\( \text{x} \) 557.77 Å and Si\( \text{xii} \) 520.60 Å are therefore affected by the volume blocking within high-lying extensions, where the absorption plays a negligible role. But volume blocking does not affect the TR lines like O\( \nu \) 629.7 Å and with such low \( \tau_{\text{H}^\alpha} \) the vertically extended EUV extension of the EUV filament cannot absorb the radiation of the TR line O\( \nu \). The darkening of this line is however due to the absorption since O\( \nu \) is not darkened. To explain this observation and results of our modelling, one could consider a possibility that both high-lying optically thin structures proposed by Anzer & Heinzel (2003) as well as low-lying parasitic dips filled with a cool optically thick plasma proposed by Aulanier & Schmieder (2002) co-exist within the filament channel.

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