HIERARCHY OF SPATIAL SCALES IN UV PROMINENCES

B. SCHMIEDER\(^1\)
\(^1\)Observatoire de Paris, Section de Meudon, DASOP, F-92195 Meudon Principal Cedex, France

J. E. WIJK\(^2\)
\(^2\)ESA, Space Science Department - Sc, ESTEC Postbus 299, NL-2200 AG Noordwijk, The Netherlands

and

K. P. DERÉ\(^3\)
\(^3\)E. O. Hulburt Center for Space Research, US Naval Research Laboratory, Washington DC 20375-5352, U.S.A.

Abstract. Ultraviolet spectra of a quiescent prominence observed with the High Resolution Telescope and Spectrograph (HRTS) are analyzed. Different techniques lead to greatly different spatial scales for the prominence structures. The UV spectra show strong variations in intensity and Doppler shift on scales larger than 1700 km. Spectroscopic diagnostics employing line intensity ratios indicate the existence of scales between 400 m to some hundred kilometers. We attempt to interpret various aspects of the prominence intensities and velocities with a multiple thread model.

Key words: Sun – Prominences – UV radiation

1. Introduction

Solar prominences are known to contain plasmas a hundred times cooler and a hundred times denser than the surrounding coronal plasma. Prominence plasmas with temperatures between \(2 \times 10^4\) and \(10^6\) K are called the prominence transition region (PTR). The ongoing debate on the structure of the PTR is focused on a few central questions like: Does the PTR surround each cool thread as observed in H\(\alpha\), or is it concentrated in separate iso-thermal threads? The answers to these questions help determine the formation mechanisms of prominences with respect to the energy balance.

During its first rocket flight the HRTS - High Resolution Telescope and Spectrograph (Bartoe and Brueckner 1975) - recorded ultraviolet spectra in the 1175 – 1715 Å range of a prominence. These spectra allow us to compute various physical parameters in the PTR such as the electron density, the emission measure and the thermal and non-thermal velocities on small spatial scales (\(\sim 1''\)).

2. UV Fine Structures in Prominences

More than ten resonance and intercombination lines from six elements were detected in the prominence. The temperatures of formation of these lines

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Fig. 1. (a) The CIV intensity along the slit. The symbols differentiate three of the structures (squares - structures I+II, triangles - structure III, and circles - structure IV). Each pixel corresponds to 0.5". (b) Intensity versus Doppler velocity and (c) intensity versus non-thermal velocity.

span the interval $10^4$ to $10^6$ K. Many transition region lines are quite strong while usually strong chromospheric lines such as CI and FeII are faint. A detailed analysis of these spectra has been presented previously by Wiik et al. (1993).

To analyse the structures of the prominence, we use the parameters derived from the three moments of the profiles (Dere et al. 1984): the integrated intensity (intensity), the net line shift (Doppler velocity), and the line width from which the non-thermal velocity has been derived. These parameters are presented, for a selected line (CIV), in Fig. 1. The intensity structures seen in Fig. 1a, labelled I-IV, appear to be discrete, separate structures from their appearance in the spectra. Their sizes are typically 2.5 – 5" and are significantly larger than the spatial resolution of the HRTS (0.8").
A good correlation is obtained between velocities from lines of different temperatures. Coherent motions over spatial scales of \( \sim 5'' \) along the slit are observed. The velocities are not distributed randomly in each structure suggesting real bulk flow. Due to the sign reversal of the velocities at the points of maximum intensity in the structures, shear or twisted motions are suspected. The high altitude component, structure I, shows velocities as high as 28 km s\(^{-1}\) while the observed non-thermal velocities in this structure are relatively low (Fig. 1b, c).

3. Physical Parameters of the PTR

From a number of pressure sensitive line ratios an average pressure of \( N_e T_e \sim 10^{16} \text{ cm}^{-3} \text{ K} \) has been derived (Wiik et al. 1993). The corresponding mean electron density is \( N_e \sim 10^{11} \text{ cm}^{-3} \) at \( T_e = 10^8 \text{ K} \). Such high value is typical for active prominences (Poland and Tandberg-Hanssen 1983, Widing et al. 1986; Dere et al. 1982). Complementary information on the prominence plasma is contained in the emission measure \( EM(T) = N_e(T) N_H(T) \Delta l \) which is derived from a spectral line intensity through: \( I = \epsilon(T) EM(T) \), where the path length \( \Delta l \) is understood to the total path length along the line-of-sight where the temperature is within roughly a factor of 2 of the peak of the emissivity \( \epsilon \). Incorporating the derived densities, path lengths \( \Delta l = 400 \text{ m} \) are found for C IV, for example.

The intensity ratio of doublets from ions such as C IV and Si IV is very sensitive to the optical depth. In most pixels along the slit, the ratio of the C IV intensities is equal to 2.0 corresponding to optically thin conditions. Only in the central part of structure II, we measure a ratio equal to 1.8 corresponding to an optical depth at line center of 0.6 (Dere and Mason 1993). For a density of \( 10^{11} \text{ cm}^{-3} \), a path length \( \Delta l \) of 40 km is derived. This constitutes an upper limit on the path length based on the considerations of optical depth because most of the profiles appear to be optically thin. The path length is considerable larger than the path length derived from the emission measure analysis. The discrepancy between the path lengths may indicate non-uniform electron densities along the line-of-sight such that \(< N_e >^2 \neq < N_e >^2 \) where the brackets \( <> \) indicate an average along the line-of-sight.

4. Multiple Thread Model

Multiple thread models have been considered in the past to interpret optical spectra of prominences (Zirker and Koutchmy 1990, 1991; Mein and Mein 1991; Mein et al. 1994). The indication of subresolution spatial scales in the UV data suggests the applicability of such a model to the present observations. The appearance of a highly blueshifted structure with low non-thermal
velocity and low intensity (structure I in Fig. 1) lends further support to this idea. We now develop quantitative predictions of the correlation expected between line intensity, velocity and non-thermal velocity based on a multiple thread model and compare these with the observations.

We assume the prominence consists of a set of identical threads, each giving rise to the same intensity. Each thread has an intrinsic non-thermal velocity (the same for all threads) and the velocity of the threads is characterized by a random gaussian distribution. Each line profile is then integrated through a discrete number $N$ of these threads. The observed line width is given by the combined width of the thermal $\Delta \lambda_{th}$, the instrumental $\Delta \lambda_{inst}$, the intrinsic non-thermal $\Delta \lambda_{ntv}$, and the random thread velocity distribution $\Delta \lambda_{thread}$. Weaker profiles should show the largest variations in bulk velocity and the most intense should show little net line shift and only small variations in line width about some average value. To derive an initial prediction, we assume that structure I in Fig. 1 consists of a single thread with an intrinsic non-thermal velocity for the thread of $10 \text{ km s}^{-1}$ as observed. The CIV $\lambda 1548$ intensity for a single thread is $10 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. If all the threads have the same intensity the number of threads would be simply the intensity of each pixel divided by the intensity of a single thread.

4.1 Gaussian distribution of threads

For a Gaussian distribution of threads, the rms distribution of velocities obtained from profiles that are the result of $N$ threads in the line-of-sight is equal to $\Delta \lambda_{thread}/\sqrt{N}$ where we expect $\Delta \lambda_{thread}$ to be equal to the average
non-thermal velocity. For C IV this is $18 \text{ km s}^{-1}$. The rms distribution calculated from the above formula can be compared to the observed distribution of C IV bulk velocities. In Fig. 2a we have plotted the rms distribution of velocities for all pixels that correspond to a given number of threads. The solid line corresponds to $\Delta \lambda_{\text{thread}} = 18 \text{ km s}^{-1}$ but a better fit to the data is found for values between 6 to 15 km s$^{-1}$. In regions with many threads along the line-of-sight ($N > 10$) the velocity dispersion of the contributing pixels is greater than in regions of intermediate number of threads along the line-of-sight. This may indicate a variable $\Delta \lambda_{\text{thread}}$ or that the intensity of single threads is not constant along the line-of-sight. The large velocity gradient across the high intensity large scale structure (structure II in Fig. 1) could also lead to large distribution of line shifts for pixels with many threads.

### 4.2 Random distribution of threads

It would be also possible to predict certain characteristics of the non-thermal velocities expected from a multiple thread model. By randomly generating a set of $N$ velocity values corresponding to the $N$ threads producing the profile, the distribution of non-thermal velocities expected for a given $\Delta \lambda_{\text{thread}}$ can be calculated. We have performed such calculations for $N$ threads where $N$ goes from 1 to 15 (Fig. 2b).

In order to make the model agree with the observed data (the observed non-thermal velocities) it was necessary to assume that $\Delta \lambda_{\text{thread}} = 26 \text{ km s}^{-1}$ (instead of 18 km s$^{-1}$). It was again assumed that the intrinsic non-thermal velocity was $10 \text{ km s}^{-1}$. This discrepancy may be due to the fact that the fine structures are not randomly distributed as far as bulk velocities are concerned in the structures.

### 4.3 Number and dimension of structures in the line-of-sight

An estimation of the number of structures in the line-of-sight could be obtained by assuming that the non-thermal velocities are due to unresolved moving structures in the line-of-sight with a Gaussian distribution of velocity. The relation between the line shift $V$ and the non-thermal line broadening $\xi$ is then, $<V^2>^{1/2} \sim \xi/\sqrt{N}$. Using this relation we find for profiles in the intermediate to bright regions, an average number of threads equal to 30 in the hot line C IV. Likewise, we find a mean value of 15 structures in the line-of-sight for the brighter parts of the prominence emitting in cool lines such as C II.

We interpret these results as follows: the line-of-sight in the central part of the structures crosses a number of micro-structures, apparently twice more of hot plasma than of cool plasma. If we assume that the structures have a circular form with diameter equal to $D = 3500\text{ km}$, and that the fine structure is distributed homogeneously, the upper limit of the size of these micro-structures $d$ may be simply derived from the ratio between the
volume contributing to one pixel \((\pi(0.8''/2)^2D)\) and the volume occupied by the subresolution structures \((N\pi(d/2)^2l)\), \(d = 0.8''\sqrt{D/Nl}\), where \(l\) is the effective length of the subresolution structures. In the case of 30 hot lines in the line-of-sight we get \(d \approx 100\text{ km}\) for threads parallel to the line-of-sight \((l = D)\) and \(d \approx 250\text{ km}\) for threads normal to the line-of-sight \((l = 0.8''\).

5. Conclusion

Using the high quality spectra of a prominence observed with HRTS a number of physical parameters for the PTR plasma has been derived (Wiik et al. 1993). We have summarized in this paper the main results concerning the definition of scales of prominence fine structures, showing the uncertainty of the physical parameters involved in the filamentation of prominences. The spatial scales of the prominence structures are larger than 2.5'' (FWHM) which is greater than the spatial resolution of the instrument. A comparison of the densities derived from pressure sensitive line ratios with the emission measure leads to spatial scales of 400 m. A similar comparison with the optical depth in C IV indicate spatial scales 100 times greater. These small scale lengths seems a general characteristics of the transition region (Dere et al. 1987, Dere and Mason 1993). The analysis of the behaviour of the UV line profiles in the prominences suggest the presence of multiple subresolution threads along the line-of-sight. We have proposed a method based on a multiple thread model to interpreted these profiles. Considering the simplicity of the model, a number of aspects of the distributions of intensity, velocity and non-thermal velocity were reproduced, although not always self-consistently. The number of threads contributing to each pixel could be about 15 at temperatures near lines formed at \(2 \times 10^4\text{ K}\) and about 30 in transition region lines.

References

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