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Velocity Vector, Ionization Degree, and Temperature of Prominence Fine Structures Observed by Hinode/SOT

B. Schmieder,[1] P. Mein,[1] R. Chandra,[1] G. Molodij,[1] P. Heinzel,[2] A. Berlicki,[2] P. Schwartz,[2] F. Fárník,[2] N. Labrosse,[3] U. Anzer,[4] and T. Watanabe[5]

[1]*Observatoire de Paris, LESIA, 92195 Meudon Cedex, France*

[2]*Astronomical Institute, Academy of Sciences, Ondřejov, Czech Republic*

[3]*Department of Physics and Astronomy, University of Glasgow, Scotland*

[4]*Max Planck Institut, München, Germany*

[5]*NAOJ, Mitaka, Japan*

Abstract. Prominences have been successfully observed by Hinode in April 2007 exhibiting a strong dynamics of their fine structures. The dynamics of a prominence is a challenge to understand the formation of cool prominence plasma embedded in the hot corona. Combining simultaneous observations obtained in Hα with Hinode/SOT and the MSDP spectrograph operating at the Meudon solar tower, velocity vectors have been derived. The Doppler-shifts of bright threads are of the same order as the velocities measured perpendicular to the line of sight. This suggests that the vertical structures of the prominence could be a pile up of dips in magnetic field lines viewed in 3D. Using Hα, Hinode/XRT and TRACE data, the hydrogen ionization degree has been determined to be 0.5-0.8, and the optical thickness in Hα between 0.2 and 1.3. The Extreme Ultraviolet Imaging Spectrometer (EIS) on Hinode produced images of the prominence in 11 selected lines with formation temperatures between $\log(T) = 4.7$ and $\log(T) = 6.1$. We comment on the absorption, emissivity blocking and emission involved for interpreting the different structures of the prominence in terms of the temperature and density.

1. Introduction

Hinode/SOT (Hα, Ca II H) movies of hedgerow prominences show tremendous dynamics with downflows along bright vertical-like thread and upward moving dark features called bubbles or "plumes" (Berger et al. 2008). The aim of this paper is to determine physical quantities such as the velocity, ionization degree and temperature in order to constrain models of formation and stability of quiescent prominences. For that purpose, we used the coordinated observations of a hedgerow prominence obtained during JOP 178 (HOP111) (from April 24 to 26, 2007) with space instruments TRACE and Hinode/SOT, EIS, XRT and the ground-based spectrograph (MSDP) operating on the Meudon solar tower.

2. Counterstreaming in a Hedgerow Prominence

The high spatial and temporal resolution of SOT/NFI Hα images allows us to compute the transverse velocities using the time slice method, while the MSDP provides the line-of-sight velocities or Dopplershifts (Schmieder et al 2010). These velocities are of the same order. The bright threads exhibit velocities up to ± 10 km s^{-1} and up to 24 km s^{-1} around the dark rising bubbles. These measurements correspond to inclined structures relative to the vertical with angles between 30° to 90°. The vertical-like fine structures observed with SOT/NFI in Hα are in fact not straight threads like loop legs. They give impression of fuzzy structures and moving on side way from time to time. The LOS maps show clearly a vertical velocity pattern with alternative blue and redshifted strands, relatively stable within the scale of half an hour (Fig. 1). Schmieder et al. (2010) proposed that the prominence material is not flowing in vertical structures but in inclined threads, bright due to the integration along the line of sight. The vertical-like structures could correspond to material piled up in shallow dips aligned to magnetic field lines (Heinzel & Anzer 2001). The velocity vectors could correspond to twisted structures or to counterstreaming along bundles of inclined structures.

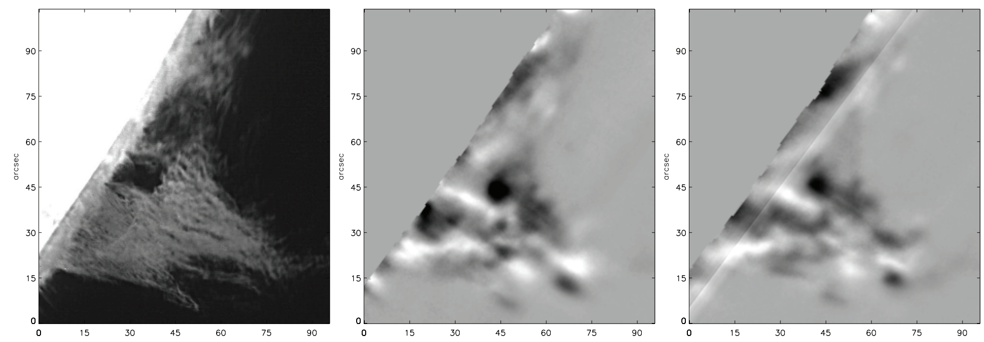

Figure 1. Hinode/SOT at 13:19 UT and MDSP Dopplershift images respectively at 13:19 UT and 13:23 UT on April 25 2007 (white/black regions correspond to blue/redshift strands.

3. Cavity of the Prominence

We distinguish a large cavity around the prominence in XRT image (Fig. 2). This cavity has a long time duration around three days (Török et al. 2009; Heinzel et al. 2008). This structure is very different from transient bubbles which last 5 min to 10 min. The large cavity corresponds to lowered coronal emission due to less abundant hot material. This mechanism is called "emissivity blocking mechanism". In TRACE images, the cavity is well visible. At its bottom, close to the limb, another dark feature corresponds to the prominence itself because of the absorption of the 195 Å line radiation. The absorption of the coronal line radiation is due to the photoionisation of the hydrogen, neutral helium and ionized helium.

In Heinzel et al. (2008) the optical thickness is derived from intensity ratios between the prominence and the nearby corona using TRACE observations and by subtracting the effect of emissivity blocking computed from XRT images. It is assumed that the soft X-rays and the coronal line have similar emissivity in the corona (Table 1). We can also derive the optical thickness of the prominence directly from the integrated intensity of Hα observed by the MSDP and using the theoretical results of non-LTE models (Heinzel et al. 1994). The $\tau_{\mathrm{H}\alpha}$ values are equal to the τ_{195} if we take into

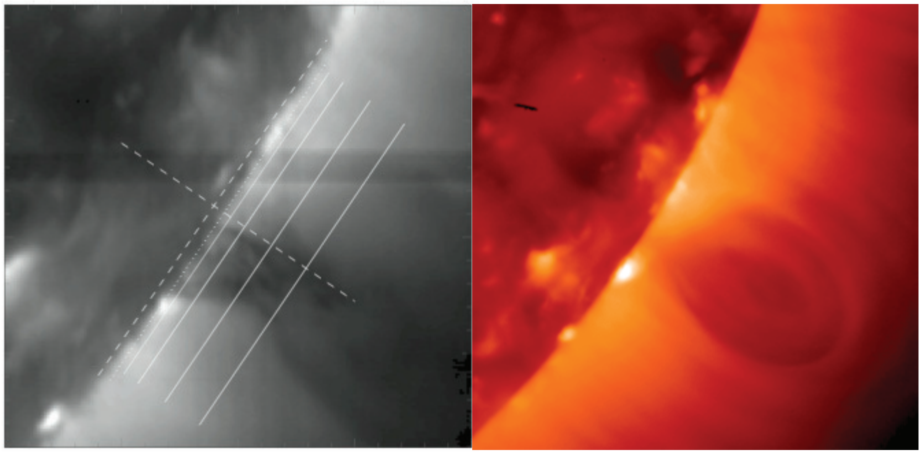

Figure 2. Observations of the cavity of the prominence on April 25 2007 by TRACE and Hinode/XRT (Heinzel et al. 2008).

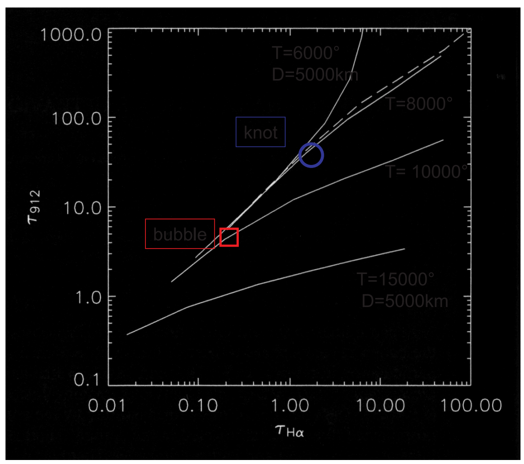

Figure 3. Correlation between τ(912Å) and τ(Hα) (Anzer & Heinzel 2005). Circle and square represent values measured in the main prominence and a bubble.

account the uncertainties of the measurements. Such a result has been demonstrated theoretically by Anzer & Heinzel (2005)(Table 1). To convert τ_{195} to τ_{912} we use the approximate relation of Anzer & Heinzel (2005).

4. Ionization Degree and Temperature

The relation between the optical thickness at the hydrogen Lyman continuum head τ_{912} and that at the Hα line center can be found using detailed non-LTE radiative transfer calculations. Anzer & Heinzel (2005) developed a grid of such models. Using the results of the observations presented in Table 1, we are able to inverse the problem and derive the characteristics of the models (T, i, D) which best fit the observations. According to the curves of Anzer & Heinzel (2005), reproduced in Fig. 3, the two points

Table 1. $E(\mathrm{H}\alpha)$ Integrated Hα intensity in 10^5 egs, $\tau(\mathrm{H}\alpha)$, and $\tau(195$ Å) optical thickness derived from TRACE and EIS data, τ(912Å) optical thickness at the head of H Lyman continuum, (i) hydrogen ionisation degree.

Structure	E (Hα)	$\tau_{\mathrm{H}\alpha}$	τ(195 Å) TRACE	τ(195 Å) EIS	τ(912 Å)	i
Prominence	1.11	1.3	2.00-0.95	3-1.12	25-40	0.5 - 0.6
Bubble	0.23	0.2	0.25-0.17	0.55-0.37	5	0.7 - 0.9

corresponding to the main prominence (knot) and a dark bubble fit the following models:

Main prominence: $T = 6000-8000$ K, and $i = 0.5$ - 0.6
Bubble : $T = 6000-10000$ K, and i =0.7 - 0.9
The curves have a weak dependence on the temperature and D, the geometrical thickness .

5. Absorption and Emission in EUV

The EIS spectrograph aboard Hinode observed many lines in the range 185-280 Å. Many of these lines are blended (Young et al. 2007). Transition region lines emit radiation from the PCTR (prominence corona transition region). On the other hand , the coronal line radiation (like Fe xii 195 Å) is absorbed by the helium Lyman continuum (Table 1). This is well visible on the EIS images (Fig. 4). Figure 5 shows some examples of profiles of the lines obtained in different boxes shown in Fig. 4 in the prominence, below the prominence and corona. Unfortunately, the He ii line at 256.32 Å is blended by two coronal lines (Si x at 256.37 Å and Fe xii at 256.41 Å). We need to disentangle all these blend effects on the He ii line profiles (Labrosse et al 2010, in preparation).

It is difficult to conclude on the nature of the atmosphere below the prominence and if it corresponds to bubbles like is described in Berger et al. (2008). The 195 Å brightness observed in the dark area in Hα (bubble) could be due to the foreground and background corona visible through a low density region or slightly absorbed by the plasma inside the region if it is cool. Hα intensity is nevertheless too weak to allow us to measure the LOS velocity and the transverse velocity field. We are not able to see if the material is moving up in the bubbles. Is the plasma hot? That is difficult to guess. The dark areas seen below the prominence in Hα on April 25 2007 are certainly magnetized regions with lower density and that is the main reason of their ascending phase. On the next day (April 26 2007), it is not so clear to see such phenomena in the Hα images.

6. Conclusions

The Dopplershifts derived from the MSDP observations show that the hedgerow prominence observed by Hinode/SOT are not vertical structures in the plane of the sky. The measurements suggest that these structures may be a pile up of dips on more or less

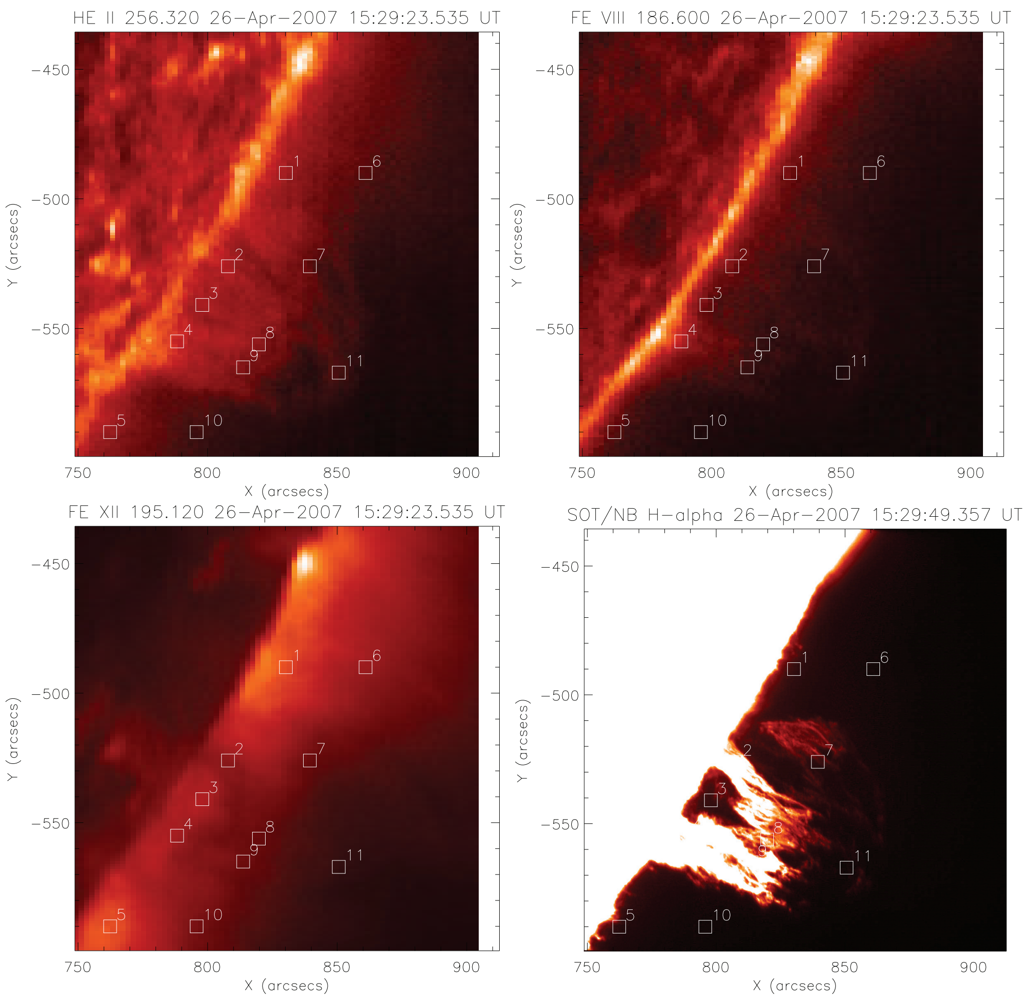

Figure 4. Hinode/EIS rasters between 14:52 and 16:42 UT on April 26 2007. The boxes show the locations where mean profiles have been computed.

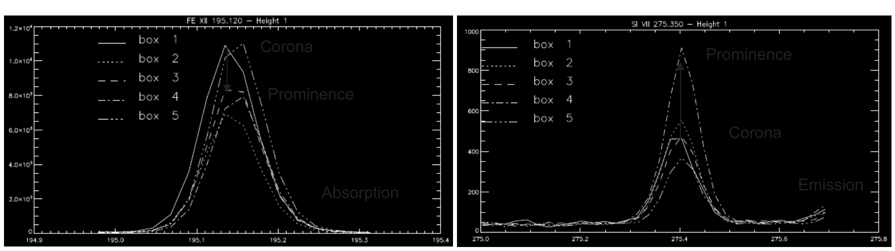

Figure 5. Profiles of Fe xii and Si vii in the boxes 1-5 presented in EIS rasters in Fig. 3.

horizontal magnetic field lines in a 3D prospective. We have to be cautious to interpret the SOT movies. The velocities up to ± 10 km s^{-1} are very small compared to free fall (100 km s^{-1}). The nature of the dark bubbles rising with velocities reaching 24 km s^{-1} from the limb is unknown. The physical quantities of the prominence material and the material seen through the bubble can fit with standard models. This suggests that the bubble is some kind of a cavity with less coronal plasma and is more magnetized than the surrounding. This could be the reason why it is rising. The "plumes" can be just an empty space between moving side way bundles of threads. It is still intriguing why they seem to rise inside the prominence.

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