A study of a macro-spicule and a transition region explosive event in a solar coronal hole

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Aims. Spicules and the higher macro-spicules (jet-like structures seen at the solar limb) are believed to be the dominant mechanism for mass ejection in the higher solar atmosphere outside active regions. But what is the connection between them and other small-scale structures in the Sun's atmosphere, like for example transition region explosive events, is not known yet.
Methods. Our data are temporal series spectroheliograms of EUV emission lines from two ions (N IV 765 Å and Ne VIII 770 Å), taken with the SUMER (Solar UV Measurements of Emitted Radiation) spectrograph on SoHO (the Solar and Heliospheric Observatory). SUMER's good spatial, spectral and temporal resolution allowed us to have one of the most detailed studies of these small-scale structures over a range of transition region temperatures.
Results. Our study reveals that a macro-spicule seen off-limb looks similar to a transition region explosive event, especially in the map of the lines' full width at half maximum (FWHM). The macro-spicule seen in the low transition region N IV line (≈140 000 K) is also visible in the higher temperature Ne VIII line (≈630 000 K). Also, the jet seen on-disk in the N IV line heats and accelerates plasma to the higher Ne VIII temperature, traveling probably along the local (presumably open) magnetic field line.

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1. INTRODUCTION

We know that the fast solar wind originates from coronal holes (Krieger et al., 1973), regions in the corona with one dominant magnetic polarity and open field lines. But to find out what are the features "inside" coronal holes that generate the steady release of the fast solar wind, we need to correlate plasma motions with fine structures seen from the solar transition region down to the chromosphere, namely "small-scale transient events". Here we concentrate on just two types of such events: macro-spicules – off-limb; transition region explosive events (TREEs) – on disk.

Spicules are common jet-like features seen above the Sun's limb with typical lengths of 5 000 to 15 000 km and lifetimes of 1 min to 10 min (Budnik et al., 1998; Wilhelm 2000a; Wilhelm 2000b). Giant spicules, also named macro-spicules, are observed to reach heights larger than 15 000 km off-limb. Apparently, some macro-spicules live over 40 min, but, as recently seen (Xia et al., 2005), they are comprised of groups of high jets with individual lifetimes of ≈5 min. After having reached the maximum height, spicules are found either falling back into the chromosphere or fading out in the transition region. Although most of their material falls back to the Sun (Pneuman and Kopp, 1978), spicules are believed to be, outside active regions, a dominant mechanism for mass ejection into the corona.

On-disk, TREEs are identified as turbulent events and jets (Brueckner and Bartoe, 1983) and are characterized by non-Gaussian profiles with enhancements in the blue/red wings. They have line-of-sight (LOS) Doppler velocities often larger than –100 km s^{-1} and a duration of 1 min to 3 min. TREEs are associated with cancellations of photospheric magnetic flux (Dere et al., 1991) and are thought to be a product of magnetic reconnection (Parker, 1988; Roussev et al., 2001). As to what mechanism would drive the reconnection, recent studies showed that they might be modulated by either kink mode waves (Doyle et al., 2006), or by *p*-mode waves (Chen and Priest, 2006).

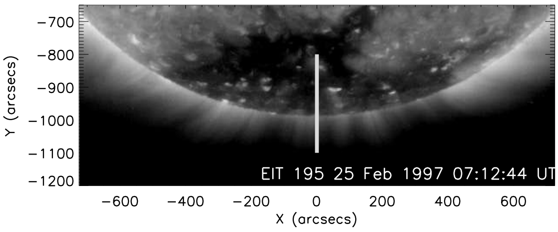

Figure 1. The solar poles in the Fe XII (195 Å) radiation on 25 Feb 1997 from the EIT/SoHO imager. The vertical white line shows the fixed position of the SUMER slit during the time series observation.

It is difficult to tell how (macro-)spicules appear on the disk when seen in the EUV, because probably due to their physical properties they are not seen against the disk's powerful background. There is only one report of a connection between TREEs and spicules (Wilhelm, 2000b), while there are also some suggestions that reconnection is linked to mottles – spicule-like structures seen on-disk (Tsiropoula et al., 1994, Tziotziou et al., 2003).

Here we pose two main questions: (a) what is the relationship between macro-spicules and TREEs? and (b) how do these events contribute to the ejection of plasma higher up, towards the corona?

To answer question (a) we need to find if these phenomena have common characteristics or not; and for question (b), we check if the jets seen in a "cold" transition region line would be seen in a hotter line.

2. THE TEMPORAL SERIES DATASET

Our data were acquired with the SUMER (Solar UV Measurements of Emitted Radiation) spectrograph on SoHO (the Solar and Heliospheric Observatory). The characteristics of our dataset are given in Table 1.

Table 1
SUMER observation taken at the Sun's south pole.

date and time [UTC]	λ [Å]
25/02/1997, 00:03–13:58	N IV 765 and Ne VIII 770

The observation presented here consists of a time series, e.g. the instrument is set to follow the temporal evolution of an area 1" (≈720 km) wide and 300" long in the southern coronal hole of the Sun (see Fig. 1), with an exposure time of 1 min, for nearly 14 h.

We study the emission line profiles for two lines: N IV 765.15 Å and Ne VIII 770.42 Å. We applied, in the first instance, a single Gaussian fitting procedure (first outlined by Dammasch et al. 1999) for both lines, from which we derived parameters such as: radiance, Doppler velocity and full-width-at-half-maximum (FWHM). We have corrected the Doppler velocity by setting its value to be zero at the limb. The "PIKAIA" software (Charbonneau, 1995) was applied to fit the TREE profiles to double Gaussians.

3. RESULTS: THE SELECTED EXAMPLES

To compare spicule-like structures seen at the limb with on-disk transient events, we selected a macro-spicule (Fig. 2) and a TREE (Fig. 3).

The three top panels of these figures are a "zoom" on each of the selected events. They are temporal series maps spanning 45 min (on the x axis, with a time resolution of 1 min) and a height in solar y of 75", with a spatial resolution of 1" (0" represents the Sun's chromospheric limb). One can see the radiance, FWHM and Doppler velocity for (a) the "cold" N IV line and (b) the "hot" Ne VIII line, as derived from a single Gaussian fitting.

In the radiance time-series maps, plotted logarithmically, the brighter colours represent higher values. For the FWHM, bright stands for higher (broader line widths), and darker, for lower values (narrower widths). The Doppler velocity maps show LOS shifts of ± 10 km s^{-1}(blue, or negative values, stand for plasma going out, while red, or positive values, for plasma coming back to the Sun). Despite the fact that at some locations even the single Gaussian fitting would give higher velocities (≈|50| kms), the reason we are plotting only values in a restricted interval is that these locations are scarce and that would make most of the values, which are around ± 10 km s^{-1}, look mainly white, with little red/blue contrast.

In the right and bottom panels we show some examples of line profiles, indicated on the upper maps by three points selected along the solar y axis: **A, B, C**; and a 5 min sequence on the time x axis: **D**.

3.1. The "zoomed-in" temporal series maps

We selected the macro-spicule by looking at the radiance in the "cold" N IV line. To find if there is any indication that plasma would reach the temperature

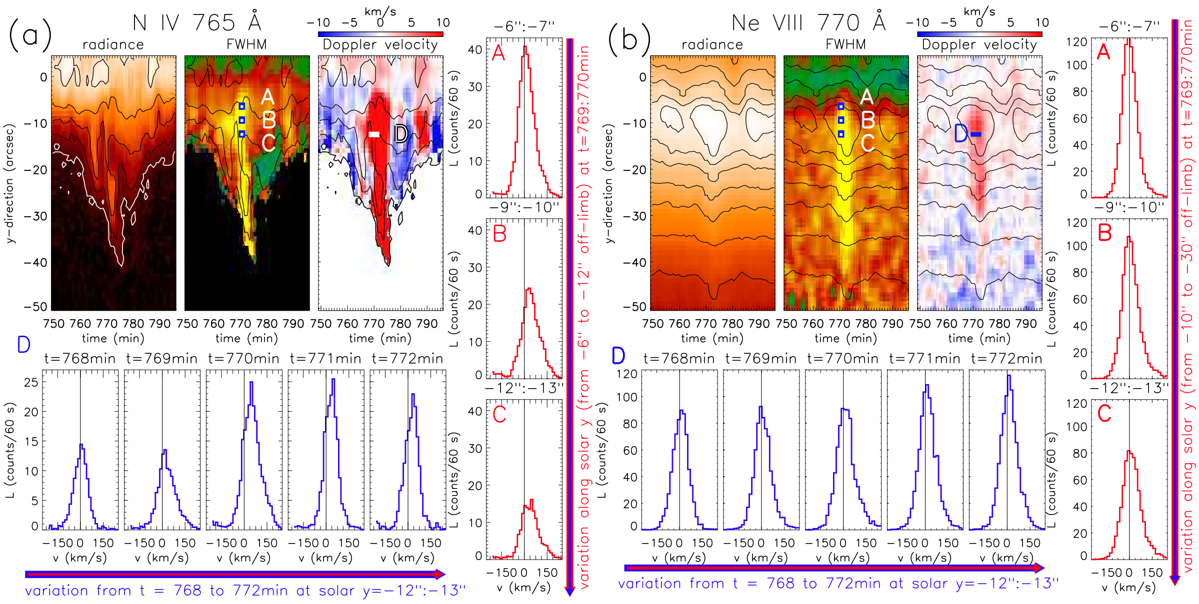

Figure 2. Time-series radiance, FWHM and Doppler velocity maps in the N IV line for a macro-spicule seen from t = 750 min to 795 min. The overlaid contours show different values of the radiance in logarithmic scale. A, B and C indicate the locations where the spectra examples are shown in the right panels, whereas D is the location along the temporal direction from where spectra are shown in the lower panels.

of the Ne VIII line, we first looked at its intensity, and we indeed saw some increase. More is seen in the Doppler velocity map, which shows a very clear blue/red structure in N IV, present also in the Ne VIII line, although more diffuse. But the most obvious indication that the N IV jet is seen in the hotter Ne VIII line is in the FWHM map. The FWHM shows strong increases, sometimes even as much as doubling in value, in both the “cool” and the “hot” lines.

The second chosen location is a zoom on an on-disk TREE (Fig. 3), which shows a small increase in the radiance, but clear blue-shifts, as well as a strong increase in the FWHM, in both lines. Interesting to notice is the 5” sliding-down of the feature seen in the “hot” line as compared to the “cold” one, indicating that the jet is traveling along the local magnetic field line, which is likely to be open, as we are observing in a coronal hole.

3.2. The line profiles: what do they tell us?

In the other panels of Figs. 2 and 3 we plot samples of spectra from locations chosen along the length of each feature on solar *y* (**A, B** and **C**), as well as along 5 min on the time axis (**D**), showing how the line profile changes in space and time. Motions on scales larger than the instrumental spatial resolution lead to the shift of the entire line profile, while thermal and non-thermal motions on scales smaller than the spatial resolution determine the profile’s shape.

Outside active regions, profiles of transition region lines are generally well represented by a single Gaussian, indicating that the small-scale thermal and non-thermal motions both follow a Maxwellian distribution in most cases. In this framework, the triggering of high-speed flows will lead to the non-Gaussian line profiles with blue and/or red wings, characteristic of TREEs (Teriaca et al., 2004).

The macro-spicule in Fig. 2 has non-Gaussian profiles with clearly increased red wings, lasting for about 5 min and being stretched for ≈50” above the limb, in both lines. At position solar *y*=–12”:–13” and t = 770 min, the single Gaussian fitting gives, for N IV, a Doppler velocity of 55 km s^{-1}, but if we use a double Gaussian, then we have two components with velocities of 45 and 155 km s^{-1}. At the same location,

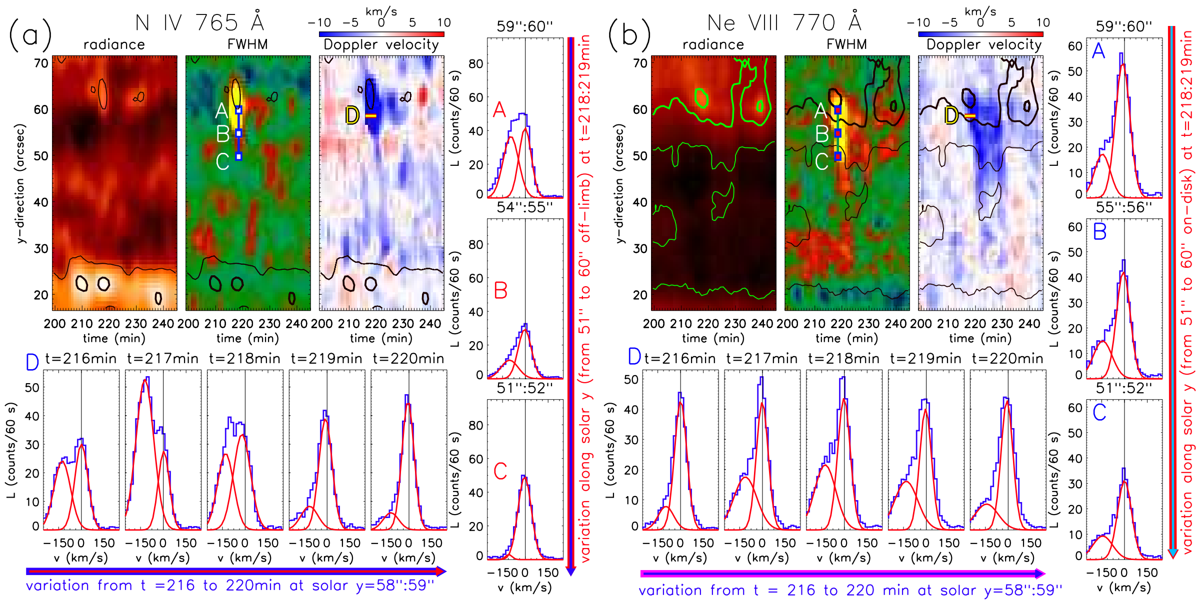

Figure 3. Similar time-series maps as to Fig. 2 but for an on-disk TREE seen from t = 200 to 245 min, at about 60” from the limb. We also show the profiles of the two Gaussian fitting for each spectrum.

for Ne VIII, a single Gaussian is shifted by 15 km s^{-1}, while a double Gaussian fitting reveals two relative LOS velocities of 5 km s^{-1}and 135 km s^{-1}.

For the on-disk TREE there is not much brightening in the radiance in any of the two lines, but the FWHM increases considerably for about 5 min, followed by another two increases in the next ≈20 min, although with lower values (Fig. 3). This “burst” with three peaks lasts for a total of ≈25 min in the “cold” line and ≈30 min in the “hot” line. This scenario might be similar to the one discussed earlier (Doyle et al., 2006) where we have inferred that closed and open field lines might undergo repetitive reconnection triggered by transverse oscillations in the closed flux tubes, or by *p*-modes (Chen and Priest, 2006).

As the shapes of the spectral lines for this TREE are so clear, we have chosen them to exemplify why the double Gaussian fitting is better than the single Gaussian, for dynamic events such as this one. In Fig. 3 we have plotted the double Gaussian fitting, while in Fig. 4 we give some examples of spectra from the same event with a single Gaussian fitting, which is obviously much worse than the double one.

For N IV, the amplitude of the second (blue-shifted) Gaussian is even higher than of the other one, at several locations. In the case of Ne VIII, the second Gaussian component looks surprisingly discernible for such a “hot” line. If we follow the evolution of the line shape from t=216 min to 220 min at solar *y*=58” to 59”, in the N IV line the blue-shifted Gaussian starts with a shift of ≈120 km s^{-1} at t=216 min (≈70 km s^{-1}in a single Gaussian fitting), that fades away about 5 min later. In Ne VIII line, the blue wing has a shift of about 100 km s^{-1} at t=216 min, that one minute latter increases to ≈130 km s^{-1}(seen only as ≈30 km s^{-1}in a single Gaussian), and reaches ≈160 km s^{-1} at t=220 min. This obviously indicates a plasma jet being accelerated and heated from the N IV formation temperature of ≈140 000 K up to the Ne VIII temperature of ≈630 000 K.

4. DISCUSSION

Macro-spicules were not often seen at high temperatures. There are only four reports on macro-spicules spotted in the Mg IX 368 Å line (blended with a Mg VII line), all detected in CDS (the Coronal Diagnostic Spectrometer) data, but the spectral resolution of the instrument did not allow good information on the line

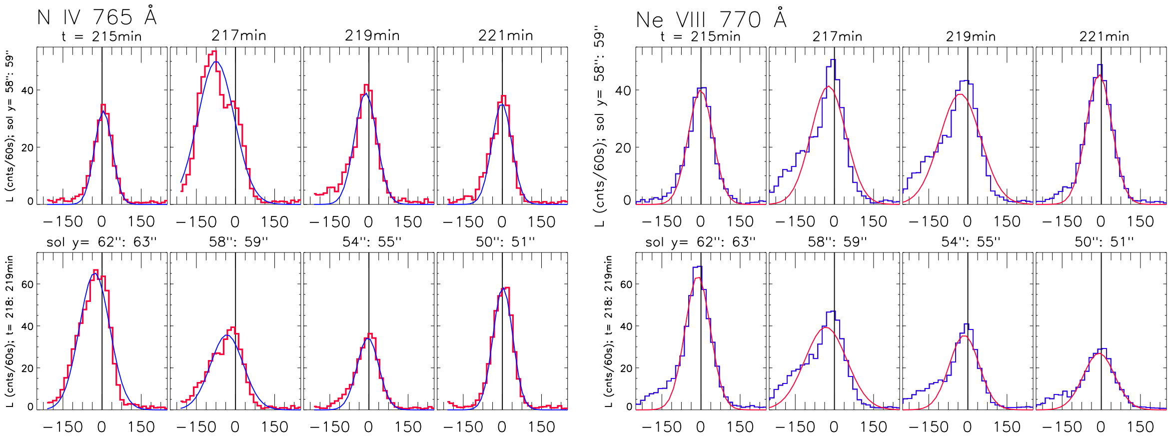

Figure 4. The profiles of the single Gaussian fitting for the TREE shown in Fig. 3 for (a) the N IV line and (b) the Ne VIII line. The top rows show the variation along time and the bottom rows, the variation along solar *y*.

profile (Pike and Harrison, 1997; Pike and Mason, 1998; Banerjee et al., 2000; Parenti et al., 2002). Here we present a much more clear indication of macro-spicular plasma heated to the Ne VIII temperature (≈630 000 K).

TREEs are not often seen at high temperatures. There was only one report of a jet in the same Ne VIII line, in a similar location, by Wilhelm et al. (2002).

The most interesting finding of this study is, undoubtedly, the presence of non-Gaussian profiles along macro-spicules and TREEs not only in the "cold" N IV line, but also in the "hot" Ne VIII line.

As regards the question about the relationship between macro-spicules and TREEs, although our study shows new common characteristics of these two events, e.g. the similarity seen in the FWHM map, more works needs to be done to clearly answer it.

We have also shown here that material being probably ejected from a reconnection event is seen in the low transition region N IV line (≈140 000 K) and very soon afterwards, in the Ne VIII line (≈630 000 K), although not exactly at the same location, but a few seconds of arc away. Moreover, we observed that the jet was not only heated, but also accelerated when it reached the higher temperature.

Although, in general terms, the Ne VIII line this is still a transition region line, in coronal holes, which are colder then other regions on the Sun, this line is thought of as representing the base of the corona. In this data-set we did not have a higher temperature line to demonstrate that the jet is reaching even higher temperatures, but if plasma is traveling along the local magnetic field line, then it may as well reach higher heights and therefore temperatures, as in a coronal hole about 80% of the field lines are open.

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