Where are the roots of the fast solar wind?

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Abstract. *A few million tones of charged particles leave the Sun every second. This continuous stream of particles - the solar wind - leaks from the Sun's inner atmosphere, escaping its gravity. How is the solar wind accelerated to hundreds of km/s, together with the chain of heating processes that generate and sustain the Sun's hot corona has so far defied a quantitative understanding, despite the multitude of efforts spanning the last half century. In our work, we analyze data acquired with SoHO (the Solar and Heliospheric Observatory) instruments: the SUMER spectrograph and the EIT imager. We look in in coronal holes, being particularly interested to find the fast solar wind origins as low as possible in the solar atmosphere. Our results indicate that we have not seen the fast solar wind starting as a steady outflow in the transition region. Instead, we see bursts of short time brightenings, possibly representing bi-directional jets (explosive events) of different scales, which, because of the open magnetic field structure found in coronal holes, could pump plasma into the corona.*

Introduction.

We know that the fast solar wind (500-900 km s^{-1}) originates from coronal holes, regions in which one magnetic polarity dominates, and, high in the corona, the field lines are open. To find what are the small-scale features responsible for the appearance of the fast solar wind, we need to correlate plasma motions with fine structures inside the coronal holes, seen from the transition region (TR) downward. If we look "under" coronal holes, we do not really see "holes", but a variety of bright transient events: spicules, explosive events, coronal jets, blinkers, etc. Some might be closely related but given different names by seeing them on disk or off-limb, at a particular wavelength or by a certain instrument. How close this relationship holds and the connection of these small-scale phenomena to the solar wind is what we are questioning and investigating.

The Data

we use were acquired with the **SUMER** (Solar Ultraviolet Measurements of Emitted Radiation) grating spectrograph and **EIT** (**E**xtreme-ultraviolet **I**maging **T**elescope) on **SoHO** (Solar and Heliospheric Observatory). There are 3 types of data: rasters (x-y solar coordinates as in **Fig. 1**), time series (time sequences of the solar y coordinate as in **Figs. 2, 3, 4, 6** & **7**) and repeated images (as in **Fig. 5**). All data are taken in polar coronal holes, on disc or off-limb, in EUV lines originating from 80,000 to 630,000 K. We study the line parameters: amplitude, velocity, width (FWHM) and the error of the fitting (χ^2). In the Doppler velocity maps, **blue** indicates plasma going out from the Sun (blue-shifts, or outflows), while **red** means plasma coming back to the Sun (red-shifts, or in-flows).

Fig. 1

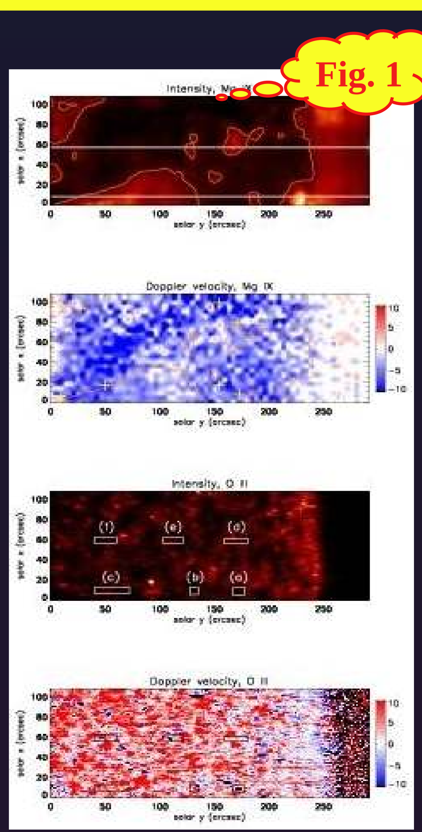


Fig. 1 shows some results from Popescu et al. (2004), where we have analysed a high spatial resolution raster in a polar coronal hole, searching for plasma outflows from coronal temperatures (in the Mg IX 706 A line, originating from 630,000 K), and also from the low transition region in O III 703 A. Although in the O III line the downward motion was predominant, it was sprinkled with outflows forming a small-scale pattern mostly at the network intersection with the inter-network cells (network boundaries).

This is the first time motion in a coronal hole at such a low height (close to the transition region base, at 80,000 K) was detected on a scale small enough to distinguish its fine correspondence with the intensity features. However, an open question following this study is whether these outflows are steady or are a result of small transient features. To check the flows' (dis)continuity, we need to analyse time series data from coronal holes in transition region and coronal lines.

The answer lies in studying the magnetic (chromospheric) network, because there we find the new emerging magnetic field lines that, by permanently interacting with the surrounding magnetic structures, create disturbances, which expel plasma higher up in the solar atmosphere.

Fig. 2 shows an example of a repetitive explosive event at a coronal hole boundary, seen on disk, in the O VI 1031 A line (T~300,000 K in the transition region). The repeated reconnection may be triggered by transverse oscillations of the flux tubes (kink modes) in the closed field line region. These oscillations periodically separate and bring together the closed and open field lines on the two sides of the coronal hole boundary (Doyle et al., 2005).

Fig. 2

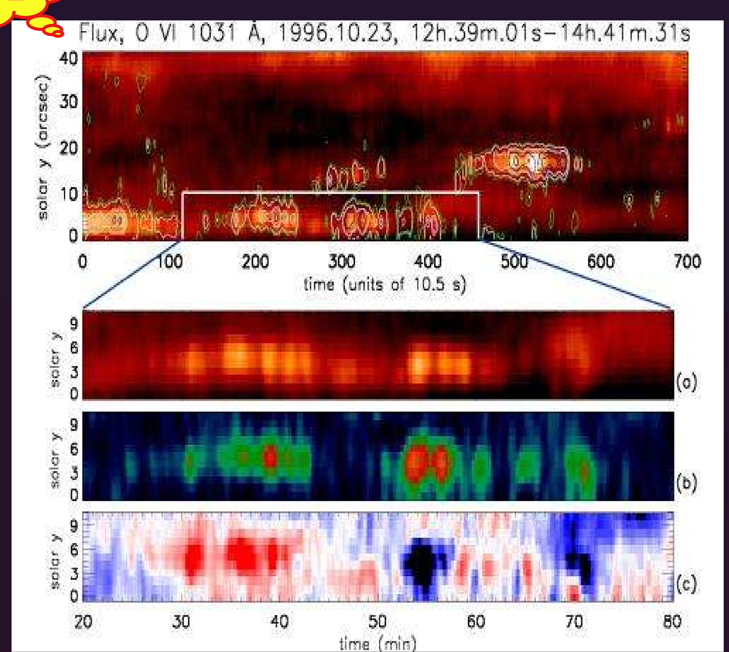
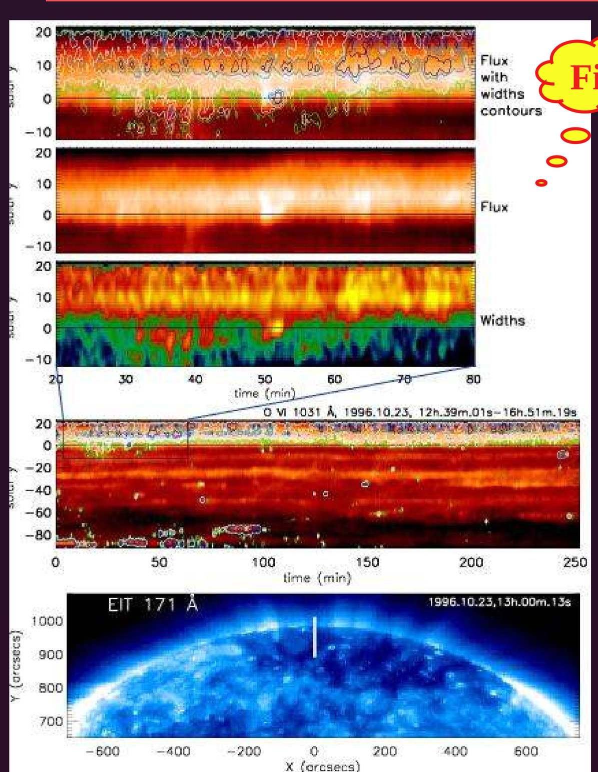


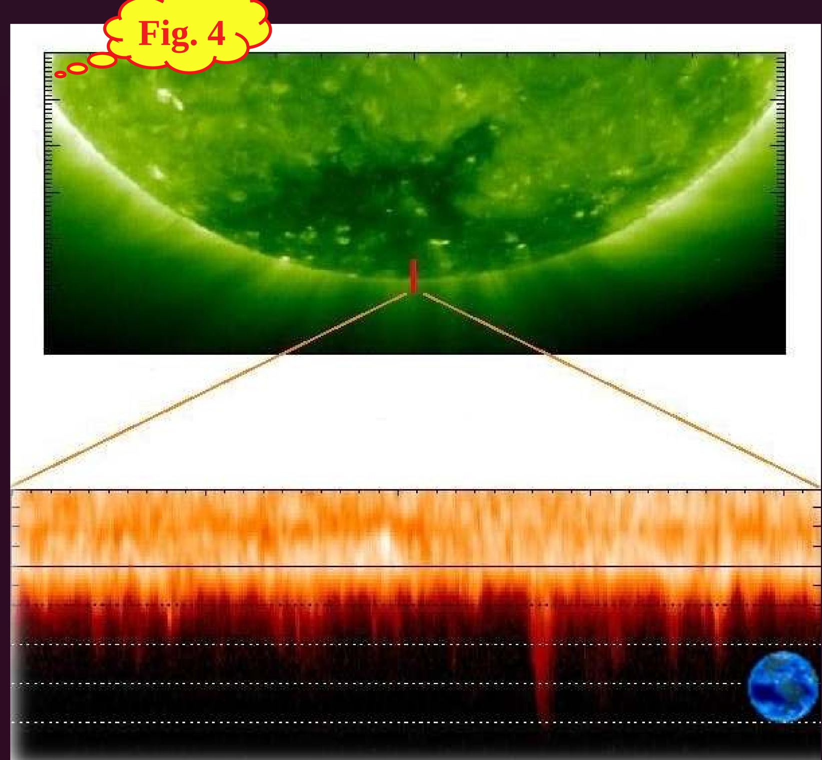
Fig. 3



How are these repetitive reconnections related to the phenomena seen at the edge of the solar disk (off-limb) and ultimately to the fast solar wind? To answer this question we need to study what happens at the solar limb.

Fig. 3 shows that the intensity and widths of the O VI line are oscillating off-limb (see the repeated increase in both the flux and the widths at ~10" off-limb). To find out if this is a similar type of phenomenon or not we are undergoing a more careful analysis in Popescu et al., in preparation.

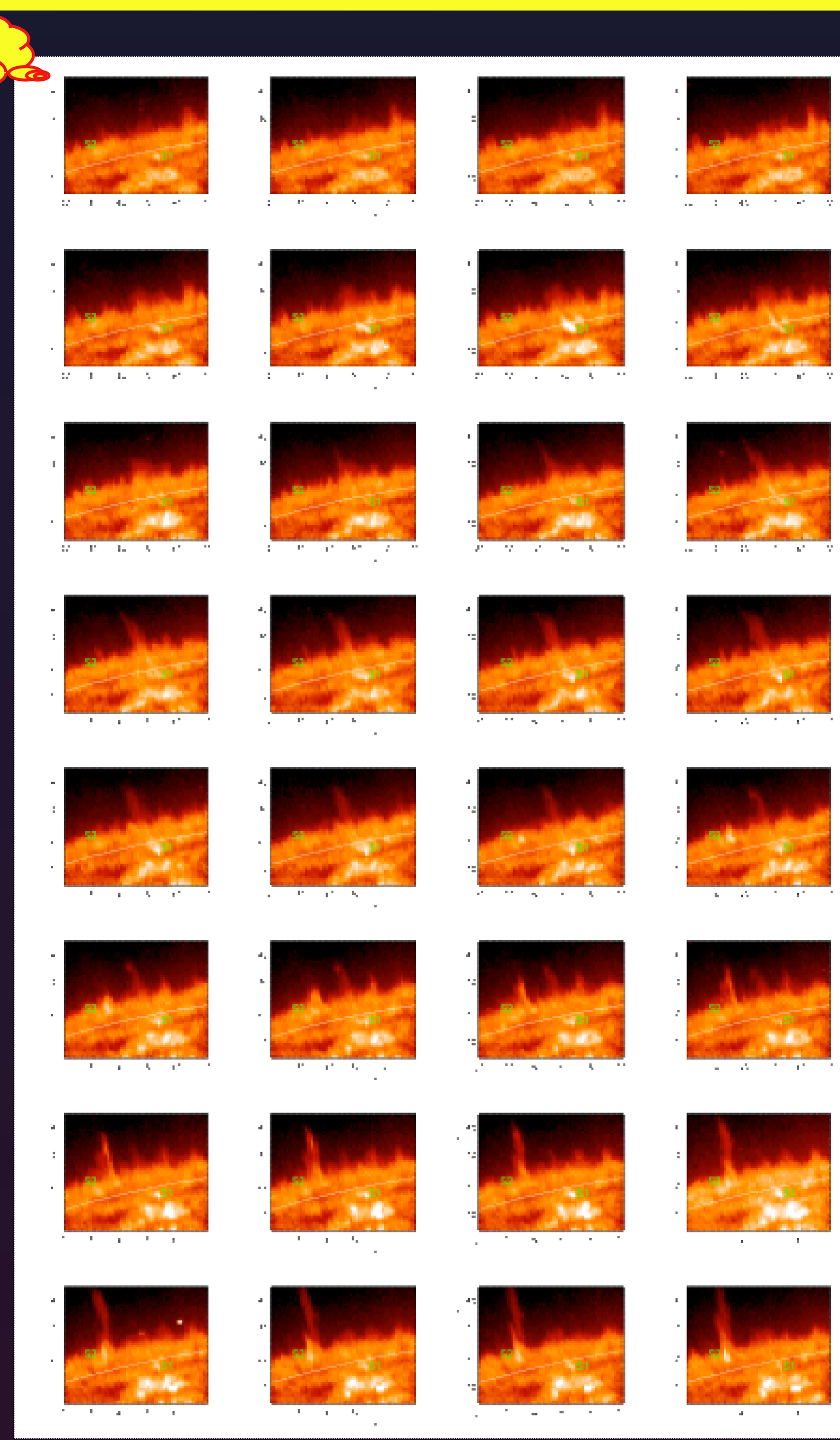
Fig. 4



The most obvious features seen at the solar limb at chromospheric and transition region temperatures are spicules. A SUMER time series (taken in the N IV 765 A line ~140,000 K) gave us the chance to see the EUV spicules with such clarity and for such long observing sequences as never seen before (Xia et al., 2005a).

The position of the slit in one of the observing sequences, as well as the temporal evolution of spicules in that location are given in Fig. 4. Spicules are probably the smallest features we can distinguish on the Sun with the current EUV instrument resolution, although they are about the size of the Earth (see plot).

Fig. 5

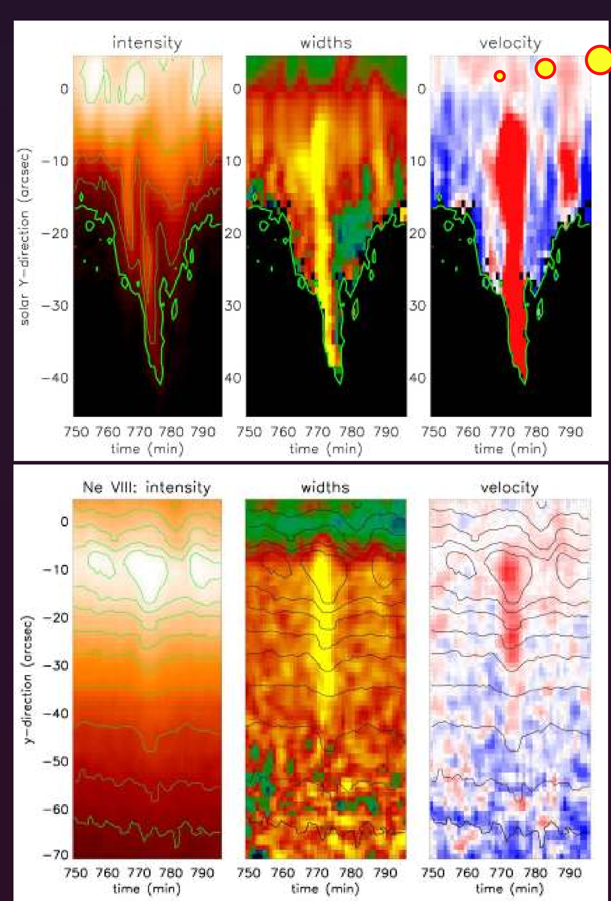


In another study (Xia et al., 2005b), we combine the time series data obtained by SUMER and EIT to study the possible connection between the events seen on the disk and the ones from the limb.

Fig. 5 presents the time evolution of a small region taken with EIT. We have investigated two sites marked as 'S1' and 'S2', which are the foot-points of two giant spicules (macro-spicules). 'S1' was driven by a series of bursts seen as brightenings of its feet. The first burst had a very short duration, but caused a huge jet with upward speed of about 100 km/s (possibly an explosive event).

Our preliminary results show a possible link between macro-spicules and blinkers (brightenings seen on-disk that last on average 17 min), as well as bursts of explosive events. However, more detailed analyses need to be done in order to establish a definitive connection between various events: EUV brightenings, bi-directional jets and (macro-)spicules occurring in the solar transition region.

Fig. 6



Another question we are asking is whether these events contribute to the heating of plasma, and possibly the transport of material higher up, in the corona. In other words, how do we prove that they might constitute the roots of the fast solar wind that would further leak along the open magnetic field lines from the coronal holes?

In Popescu et al. 2007, we show that some macro-spicules seen at transition region temperatures have a response in a hot coronal line.

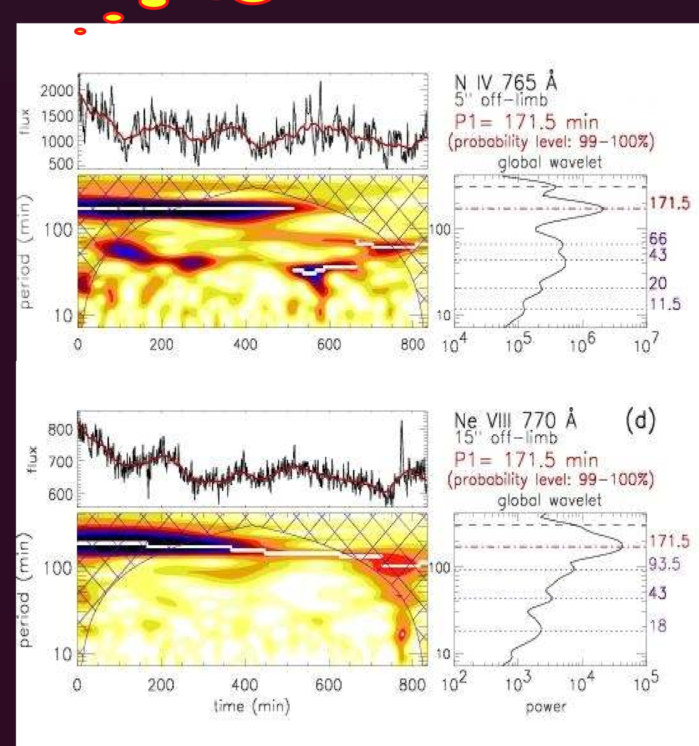
Fig. 6 presents the temporal evolution of a macro-spicule in the N IV 765 A line (top panel) that heats plasma at the temperature of the Ne VIII 770 A line (T~630,000 K, bottom panel).

How is the energy transported further up in the corona?
Do waves play any role in plasma acceleration?

To answer this question, in Popescu et al. (2005) we search for the variation of line intensity with time above a polar coronal hole and we report the detection of very long (~170 min) periodic intensity fluctuations.

Fig. 7 shows two examples of the wavelet transform applied to the temporal evolution of the intensity of the N IV and Ne VIII lines. The red curve shows the ~170 min periodic fluctuations, detected off-limb. With the acoustic cut-off frequency implying a maximum allowable period of ~90 min, it is unclear whether these fluctuations are due to waves or are the result of a recurrent magnetic reconnection process. Additionally, our data also reveal shorter periods (5-90 min), previously seen with other SoHO instruments.

Fig. 7



Conclusions

Our studies agree that the ubiquitous spicules may play a crucial role in providing plasma to the corona. We have also estimated that larger events (macro-spicules) are likely to be seen on-disk as blinkers, as well as bursts of explosive events, and some of them also heat plasma to coronal temperatures.

Depending on the magnetic field configuration from the transition region, the outward directed plasma from spicules (jets) might either come back to the Sun if it meets closed loops, or escape along the open field lines (present in coronal holes), delivering plasma into the corona and going further in the heliosphere as the fast solar wind.

In these observations, we have not seen the fast solar wind starting as a steady outflow in the transition region. Instead, we see bursts of short time brightenings, (seen off-limb as spicules) probably representing bi-directional jets of different scales, which, because of the open field structure in coronal holes, could pump plasma into the corona.

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