Evidence for magnetic reconnection along coronal hole boundaries

M.S. Madjarska[1], J.G. Doyle[2] and L. van Driel-Gesztelyi[1,3,4]

ABSTRACT

The present study reveals for the first time the existence of bi-directional jets, which are a signature of magnetic reconnection, occurring along coronal hole boundaries. The SUMER observations obtained in the N IV 765.15 Å (1.3 10^5 K) and Ne VIII 770.42 Å (6 10^5 K) emission lines in an equatorial extension of a polar coronal hole, known as the 'Elephant's Trunk' coronal hole, show small regions of a few arcsec size with strong blue- and red-shifted emission reaching Doppler shifts of up to 150 km s^{-1}, i.e. bi-directional jets. The jets' number density along coronal hole boundaries was found to be of about 4-5 times higher with respect to the quiet Sun.

Subject headings: Sun: corona—Sun: transition region—Sun: solar wind

1. Introduction

Coronal holes (CHs) are large regions on the Sun that are magnetically open and were identified as the source of the fast solar wind (~800 km s^{-1}) (Krieger, Timothy & Roelof 1973). They are visible in coronal lines as regions with a reduced emission relative to the quiet Sun. There are two types of coronal holes: polar and mid-latitudes CHs. During the minimum of the solar activity the solar atmosphere is dominated by two large CHs situated at both polar regions. The mid-latitude CHs can be either 'isolated' or connected with a CH channel to a polar CH. The latter CHs are called equatorial extensions of polar CHs (EECH).

A distinctive feature of the EECH is their nearly rigid rotation in contrast to the typical differential rotation at photospheric level (Timothy, Krieger & Vaiana 1975). Kahler &

[1]Mullard Space Science Laboratory, UCL, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK; msm@mssl.ucl.ac.uk

[2]Armagh Observatory, College Hill, Armagh BT61 9DG, UK; jgd@star.arm.ac.uk

[3]Konkoly Observatory, P.O. Box 67, H-1525 Budapest, Hungary; lvdg@mssl.ucl.ac.uk

[4]Observatoire de Paris, LESIA, FRE 2461 (CNRS), F-92195 Meudon Principal Cedex, France

Hudson (2002) give a detailed overview of the different mechanism suggested to maintain the quasi-rigid rotation of the coronal holes.

Due to these different rotation profiles at the coronal and photospheric level and the fact that CH boundaries (CHB) separate two topologically different (open and closed) magnetic field configurations, CHBs are presumably the regions where an opening and closing of magnetic field lines take place.

This reconfiguration is believed to happen through magnetic reconnection between the open and closed magnetic field lines of the CH and the surrounding quiet Sun. Despite numerous attempts at identifying any phenomenon which could be associated with magnetic reconnection along CHBs, no direct evidence has been found so far (Kahler & Hudson 2002). Kahler & Moses (1990) studied SKYLAB X-ray images of CH boundaries with a time resolution of 90 minutes and found that X-ray bright points play an important role in both the expansion and contraction of a CH. Zhao, Hoeksema & Scherrer (1999) studied the rotational characteristics of the 'Elephant's Trunk' CH (1996) (the subject of our study). They found that the CH showed nearly rigid rotation with a rate of $13\overset{\circ}{.}25$/day ($14\overset{\circ}{.}6$/day for leader sunspots). They also observed day-to-day variations of the CHBs. Brommage et al. (2000) reported that small-scale changes of the boundaries of the same CH appeared on timescales of a few hours in observations with the Extreme-ultraviolet Imaging Telescope (EIT) on-board the Solar and Heliographic Observatory (SoHO) in Fe XII 195 Å.

Besides their importance for the evolution of CHs, it has also been suggested that CHBs are the main source of the slow solar wind. The first observational evidence that streamer stalks – fine rays representing the filamentary structure of the streamer belt – are the source of the slow solar wind was provided by Woo and Martin (1997). From LASCO (Large Angle and Spectrometric Coronagraph Experiment) observations of outward-moving density inhomogeneities of denser plasma, called blobs, Wang et al. (1998) suggested that the slow solar wind (<500 km s^{-1}) originates in helmet streamer loops but with a major component originating outside the helmet streamers, i.e. from inside the CHs near the boundaries.

For the present study a search was carried out for spectroscopic observations which could potentially reveal signatures of magnetic reconnection. Equatorial coronal holes are the best candidates for such a study because of the most favourable line-of-sight. We also looked for data obtained in a sit-and-stare mode, which means that the slit is pointed over a certain solar region long enough to detect any velocity event propagating along the line-of-sight.

The objective of this Letter is to present the very first evidence for the existence of magnetic reconnection along CH boundaries as revealed by observations obtained with the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) spectrometer on-board SoHO.

2. Observational material

The data used in this work were obtained on 1996, October 19 and 20 in an EECH (Figure 1). The observations were simultaneously performed with the SUMER spectrometer and EIT.

The SUMER (Wilhelm et al. 1995, 1997; Lemaire et al. 1997) observations consist of temporal series in N IV 765 Å and Ne VIII 770 Å obtained using a $1'' \times 300''$ slit and 60 s exposure time on KBr coated part of detector B during $\sim$10 hours. The instrument was pointed at an EECH at coordinates Solar_X = $0''$ and Solar_Y = $-140''$. The observations started on October 19 at 20:22 UT and finished on October 21 at 06:50 UT. No compensation for the solar rotation was applied and therefore with the solar rotation rate at these coordinates of $\sim 9\rlap{.}''5$ the 1 arcsec slit covered an area of $\sim 95''$ on the Sun. The rest wavelength was derived from a profile averaged over a quiet Sun area.

The reduction of the SUMER raw data involves local gain correction, flat-field subtraction and a correction for geometrical distortion. The signal to noise level was determined by the photon statistics. Additionally a correction for the spectral line shift caused by thermal deformations of the optical bench of SUMER was applied (Dammasch et al. 1999).

The EIT (Delaboudiniére et al. 1995) observations analysed in this study consist of full-disk and partial-disk images with a resolution of $2\rlap{.}''62$ in Fe XII 195 Å. The partial-disk images were obtained with a cadence of 2 images per hour from 20:31 UT until 06:55 UT. However, the FOV of the EIT high resolution images covers only partially the SUMER FOV.

3. Data analysis and results

In Figure 2 we show integrated (over the spectral line with the background included) intensity images in the N IV and Ne VIII lines produced by binning over 6 spectra in order to improve the signal-to-noise ratio. The Doppler shift map was derived by applying a single Gauss fitting (Figure 2). Since one of the wings of the spectral line during a BD jet is usually predominant (in some cases both wings are equally present) the single Gauss fits shift the line centres towards the predominant wing. This result is characteristic for line profiles of inwards and outwards moving plasma, i.e. jets, and will be discussed further below. The Fe XII 195 image was obtained on October 20 at 01:06 UT and gives an overview of the coronal emission as seen by EIT. We have to note here that the binning over 6 SUMER spectra reproduces a raster which is 5 arcsec larger than the real scanned area. Therefore the corresponding position of the BD jets over-plotted on the EIT image are only approximate.

First, the position of the CHBs had to be determined. The SUMER slit observed part of the east CHB (Figure 1). In the center of the SUMER FOV inside the CH a relatively large Bright Point was present (Figure 1). That created another boundary region between the closed and open magnetic field lines inside the CH. We believe that CHB can be best outlined from the Doppler shift map as the boundaries where an abrupt change of the Doppler shift between the quiet Sun and the Bright Point (red-shift) and the CH (blue-shift) is observed. The difference in the Doppler shift between CH and quiet Sun for the N IV one is ∼5 km s^{-1}(Peter & Judge 1999).

Next, the Doppler shift map and the spectral line profiles were visually inspected for any non-Gaussian profiles which are the main characteristics of the jets' presence. Large number of such profiles were found along the CHBs. The number density of the BD jets registered in N IV (1.3 10^5 K) line is higher than in Ne VIII (6 10^5 K). This is due to the fact that only very strong events can reach higher temperature (Teriaca, Madjarska & Doyle 2002 and references therein).

The BD jets cover an area of 4-5 arcsec along the SUMER slit and have a duration from 300 to 1000 s. Their appearance along the SUMER slit is believed to depend on the orientation of the propagating jet relative to the observer's line-of-sight. In some cases the blue- and red-shifted emission was detected with an offset along the SUMER slit. More often they appear in the same pixels along the slit. We also observed a few cases where the red-shifted emission follows in time the blue-shifted emission which could simply be that the slit scanned consecutively. Typical spectral line profiles in a BD jet and CH can be seen in Figures 3 and 4, respectively, registered at the position shown with blue triangles in Figure 2. Quiet Sun region data obtained a few hours later on the same day with the same observing programme were used to compare the occurrence rate of BD jets to the ones found along CH boundaries. The rough estimation shows that the jets' number density at the CH boundaries is of about 4-5 times higher than in the quiet Sun region.

4. Discussion and conclusions

The CH discussed in the present paper has been subject of numerous studies each revealing particular features associated with its evolution. Our study gives for the first time observational evidence for magnetic reconnection occurring along its CHBs. The reconnection is evidenced by bi-directional jets having non-Gaussian profiles of both mid- and high transition region N IV and Ne VIII lines, respectively. The jet's larger number density with respect to the quiet Sun indicates their predominant presence in these regions. The strong rigid rotation of this CH (Zhao et al. 1997) creates the necessary condition for the occurrence of frequent magnetic reconnection events along the CH boundaries. The small-scale changes of the CH boundaries observed by Brommage et al. (1999) are possibly related to the evolving small-scale loop systems as revealed by the analysis of the high cadence EIT Fe XII images. A future study will explore the relation between the loops' disappearance a nd BD jets' occurrence.

Finding BD jets along CHBs supports the conclusion of Wang et al. (1998) who state that the slow solar wind originates from inside the coronal holes close to their boundaries and results from magnetic reconnection between the open and closed magnetic field lines inside and outside the coronal holes. A forthcoming study will look for a direct association of these BD jets with the outflowing plasma blobs seen by LASCO. Another ongoing study will try to confirm the results of the present study using other coronal holes (including isolated CHs which rotate almost differentially) and spectral lines covering larger spectral range.

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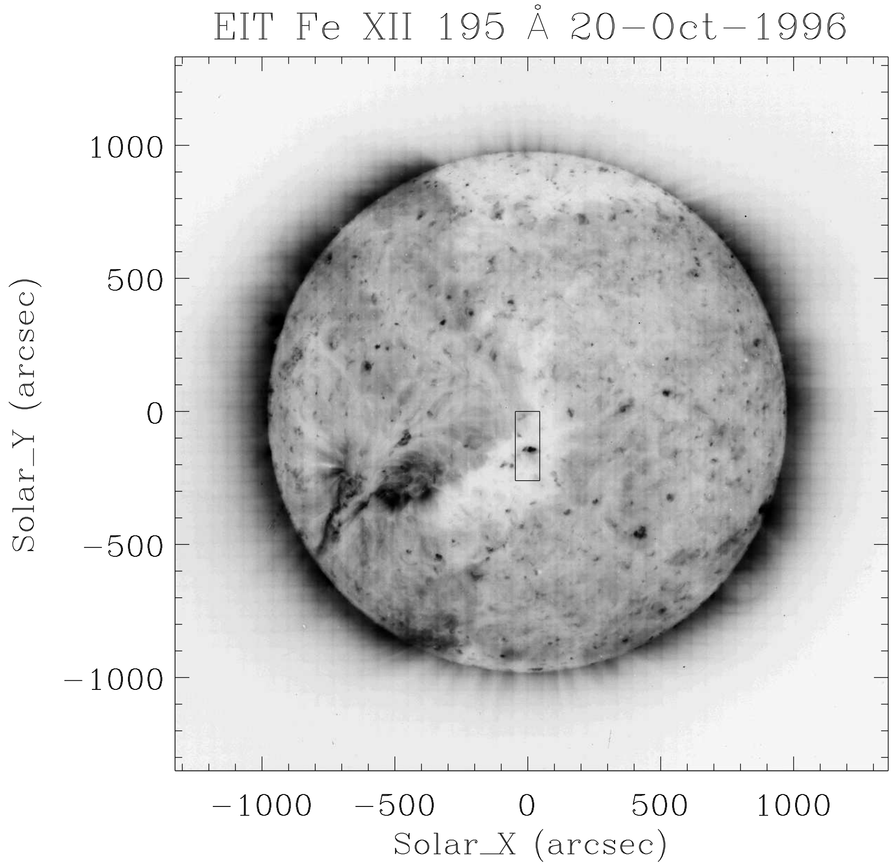

Fig. 1.— Reversed colour EIT Fe XII 195 Å image obtained on October 20 at 01:06 UT with over-plotted SUMER field-of-view.

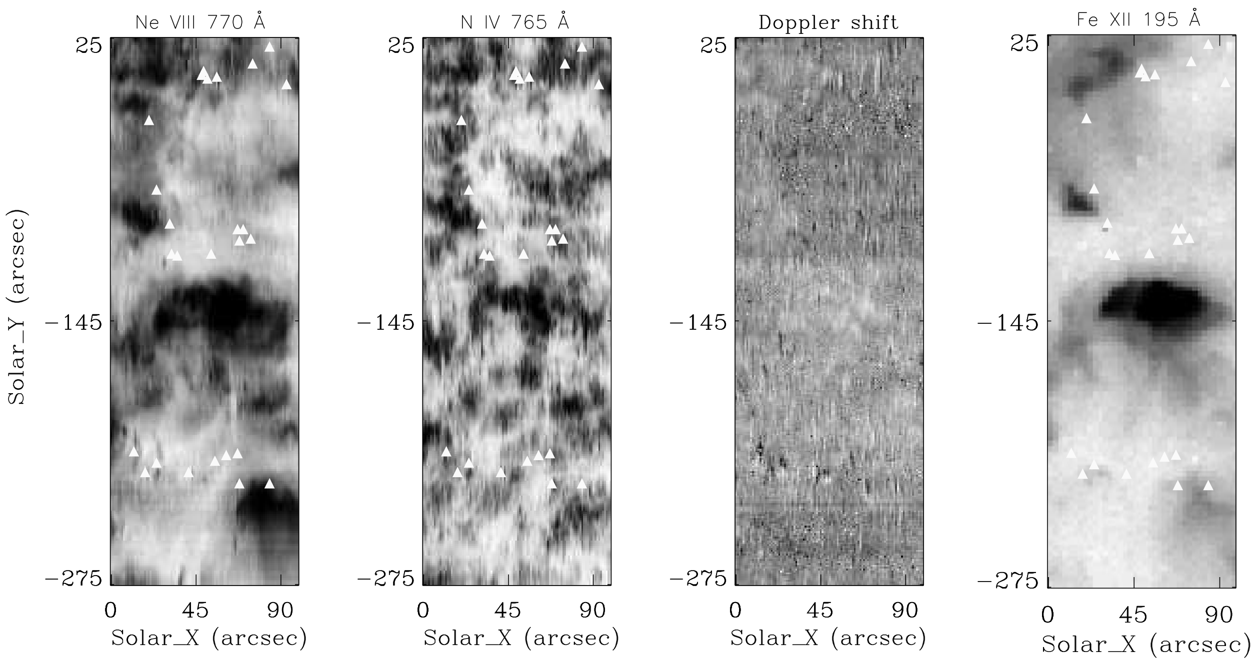

Fig. 2.— From left to right: Reversed colour intensity image in Ne VIII and N IV; Doppler shift map obtained by applying a single Gauss fit (from –30 to 30 km s^{-1}); reversed colour EIT Fe XII 195 Å image. The triangles show the positions of the BD jets.

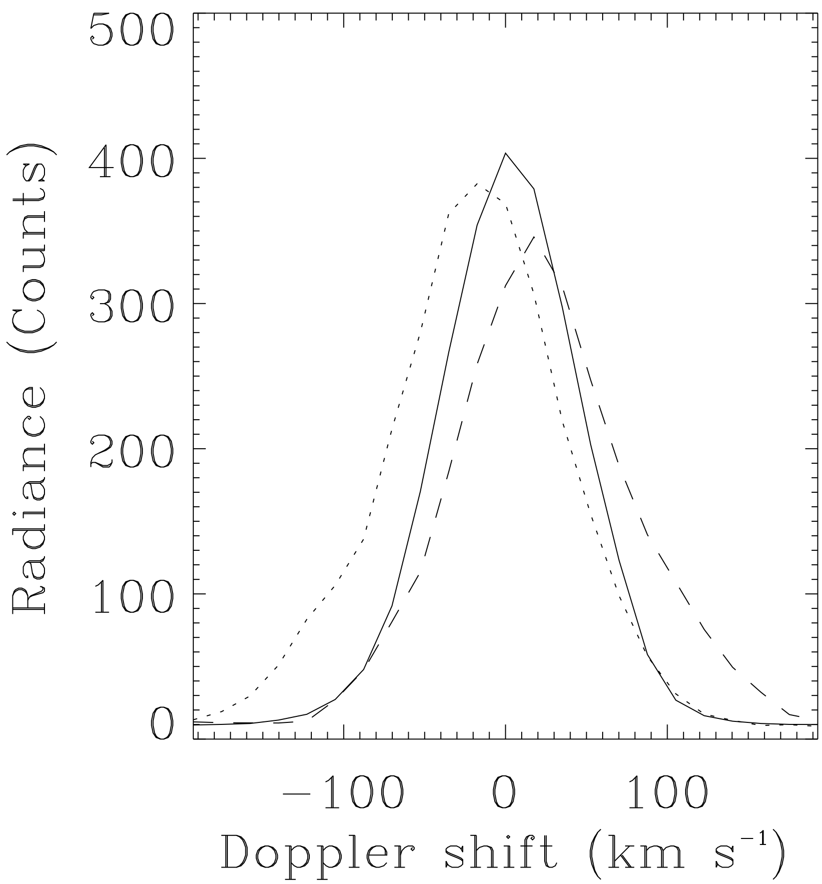

Fig. 3.— N IV line profiles of the quiet Sun (solid line); the dotted and dashed line profiles are taken from a blue- and red-shifted emission of a BD jet, respectively.

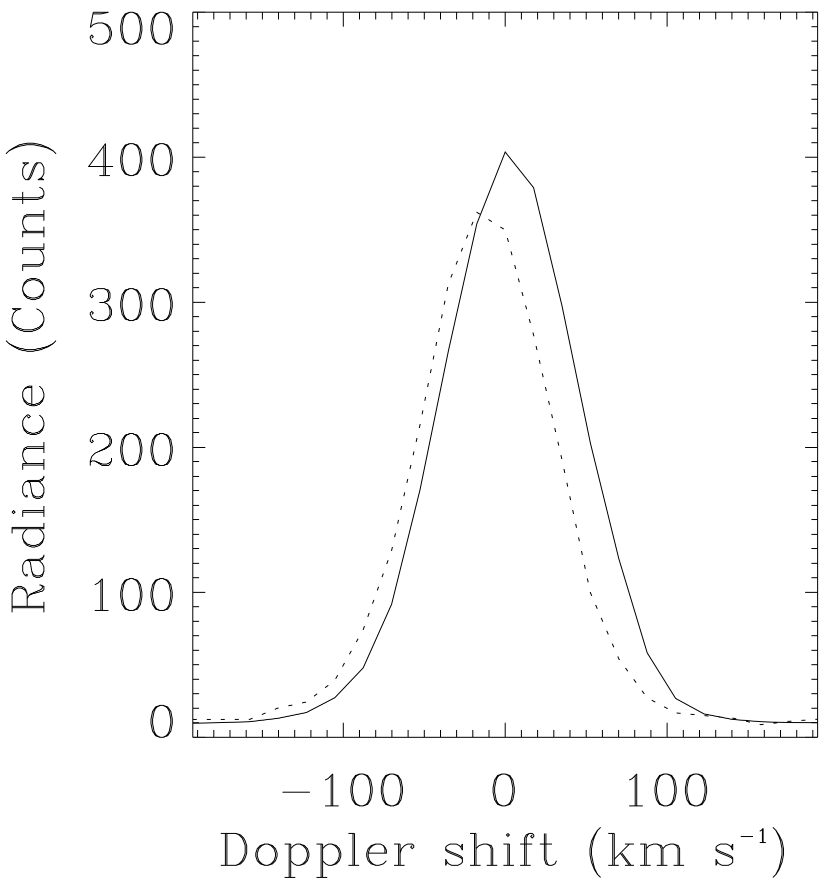

Fig. 4.— Typical N IV line profile of the CH (dotted line) and profile of the quiet Sun (solid line).