

Intermittent outflows at the edge of an active region – a possible source of the solar wind?

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Received 20 November 2009 / Accepted 9 March 2010

ABSTRACT

Context. It has already been established that the solar wind may originate at the edges of active regions (ARs), but the key questions of how frequently these outflows occur, and at which height the nascent solar wind originates have not yet been addressed.

Aims. We study the occurrence rate of these intermittent outflows, the related plasma activities beneath in the low solar atmosphere, and the interplanetary counterparts of the nascent solar wind outflow.

Methods. We use the observations from XRT/Hinode and TRACE to study the outflow patterns. The occurrence frequency of the intermittent outflow is estimated by counting the occurrences of propagating intensity enhancements in height-time diagrams. We adopt observations of SOT/Hinode and EIS/Hinode to investigate the phenomena in the chromosphere associated with the coronal outflows. The ACE plasma and field in-situ measurements near Earth are used to study the interplanetary manifestations.

Results. We find that in one elongated coronal emission structure, referred to as strand, the plasma flows outward intermittently, about every 20 min. The flow speed sometimes exceeds 200 km s^{-1} , which is indicative of rapid acceleration, and thus exceeds the coronal sound speed at low altitudes. The inferred flow speed of the soft-X-ray-emitting plasma component seems a little higher than that of the Fe IX/X-emitting plasma component. Chromospheric jets are found to occur at the root of the strand. Upflows in the chromosphere are also confirmed by blue-shifts of the He II line. The heliospheric plasma counterpart close to the Earth is found to be an intermediate-speed solar wind stream. The AR edge may also deliver some plasmas to a fraction of the fast solar wind stream, most of which emanate from the neighboring CH.

Conclusions. The possible origin of the nascent solar wind in the chromosphere, the observed excessive outflow speed of over 200 km s^{-1} in the lower corona, and the corresponding intermediate-speed solar wind stream in interplanetary space are all linked in our case study. These phenomena from the low solar atmosphere to the heliosphere near Earth in combination shed new light on the solar wind formation process. These observational results will constrain future modeling of the solar winds originating close to an AR.

Key words. solar wind – Sun: photosphere – Sun: chromosphere – Sun: corona

1. Introduction

Solar winds emanating from the solar atmosphere are generally classified into two types, the fast and the slow streams. During solar minimum, the fast solar wind is recognized to originate in the (polar) coronal holes (CHs), in particular from the magnetic funnels according to both observations (Xia et al. 2003; Tu et al. 2005a,b; Marsch et al. 2006; Tian et al. 2010) and theoretical models (Tu & Marsch 1997; Marsch & Tu 1997; Hackenberg et al. 2000; Esser et al. 2005; He et al. 2008). The slow solar wind has several possible source regions, such as the boundaries of polar CHs (Wang et al. 1990), the helmet streamers (Wang et al. 2000), the funnel-like structures in the quiet regions (He et al. 2007; Tian et al. 2008a, 2009), and the edges of active regions (ARs) (e.g., Sakao et al. 2007; Harra et al. 2008). For a comprehensive review of previous studies of plasma characteristics and magnetic features in the solar wind source regions, we refer to Marsch (2006).

The connection between the slow solar wind and the edge of an AR was suggested by Kojima et al. (1999). They traced the velocity distributions derived from interplanetary scintillation

(IPS) observations back to the magnetic source surface at $2.5 R_{\odot}$, extrapolated the open coronal field lines outward to the source surface, and then compared the velocity map and the open field map at the same height. The connection between the active region and in-situ measured solar wind was initially studied by Liewer et al. (2004), who found that higher oxygen charge states in a solar wind stream had a corresponding source in ARs rather than in CHs. Significant outflow, which supplies mass to the extended corona, was observed in the sunspot at the center of an AR (Marsch et al. 2004). Global plasma convection was found to be guided and constrained by the magnetic fields in the ARs (Marsch et al. 2008). Outflow patterns in the corner of an AR were also identified by Winebarger et al. (2001) on the basis of TRACE observations in Fe IX/X with a high cadence of 35 s. The projected speed of the intensity front was found to range between 5 and 20 km s^{-1} . Some ARs may lead to enhanced plasma outflows in neighboring CHs when the unbalanced magnetic flux from the ARs extends into the neighboring CHs (Habbal et al. 2008).

Outflows with a projected speed of 140 km s^{-1} near an AR were also detected by Sakao et al. (2007) based on observations

from XRT/Hinode in soft X-rays. These authors claimed that continuous outflow does exist, a notion based on the appearance of the very frequent outward propagation of intensity enhancements in the X-ray movie. The outflow observed by XRT has been reconfirmed by EIS observation of strong steady blueshifts ($20\text{--}50\text{ km s}^{-1}$) of Fe XII at the root sections of open field lines (Harra et al. 2008). Doschek et al. (2008) also used EIS observations to investigate strong blueshifts at the periphery of an AR, which might contribute significantly to the solar wind. On the other hand, the propagation of an intensity disturbance may be explained as a slow magnetoacoustic wave, since the inferred speed is close to or below the coronal sound speed (Robbrecht et al. 2001). But the phase speed reported in Robbrecht et al. (2001) is the projected speed component rather than the true phase speed, which may exceed the coronal sound speed.

The dynamics, which is in the chromosphere and associated with the coronal outflow from the edge of an AR, has not yet been investigated. But inside the AR, the dynamics occurring in the lower solar atmosphere has been studied extensively. Upflows of heated chromospheric plasmas, probably caused by magnetic reconnection, were suggested to supply the observed overdense material to coronal loops in ARs (Aschwanden 2001). Small-scale magnetic reconnection, which may excite transverse waves (He et al. 2009), was inferred to be ubiquitous in the chromosphere from observations of chromospheric anemone jets (Shibata et al. 2007). The chromospheric jets were sometimes found to be associated with coronal EUV/X-ray jets (Shibata et al. 1992; Chae et al. 1999; Zhang et al. 2000), which have been modeled by magnetic reconnection between newly emerging closed loop and pre-existing open field lines at the chromosphere (Yokoyama & Shibata 1995).

The longitudinal oscillations seen in the photosphere and the chromosphere are other possible phenomena connecting the activity in the lower solar atmosphere with coronal dynamics. The periodicity of the chromospheric spicules (~ 5 min) in an AR plage was demonstrated to be produced by an energy leakage of the p-mode from the photosphere along inclined field lines (De Pontieu et al. 2004). Intensity oscillations with periodicity longer than 10 min were found in polar plumes (Deforest & Gurman 1998; Banerjee et al. 2000) and coronal bright points (Tian et al. 2008b). These intensity oscillations, which propagated with a speed ($75\text{--}150\text{ km s}^{-1}$) close to the coronal sound speed, were supposed to be manifestations of slow magnetoacoustic waves.

In this paper, we investigate the possible origin of and the evolution caused by intermittent coronal outflows at the edge of an AR. We study the occurrence rate of this kind of intermittent coronal outflow. Two plasma components of that flow, soft-X-ray-emitting electrons and Fe IX/X-emitting ions, are compared on the basis of observations from XRT/Hinode and TRACE. Plasma activities in the chromosphere are studied to identify the release height of the nascent outflows. The connection between the AR-edge source and the solar wind stream near Earth will also be studied.

2. Data calibration and alignment

The datasets related to the source region at the edge of an AR were obtained by XRT/Hinode, SOT/Hinode, EIS/Hinode, and TRACE on February 21, 2007. The standard procedures of the “SolarSoftWare” (SSW) package were adopted to initially calibrate these datasets. The synoptic maps of the solar magnetic fields and CHs during one Carrington rotation were provided by NSO/KP. The in-situ measurements of the corresponding solar

wind stream were made by the MAG and SWEPAM instruments onboard the ACE satellite.

All image frames from various imaging instruments, i.e., XRT, SOT, and TRACE, were rotated to a common time selected to be 02:00 UT. In this way, the outflow feature near the AR could be tracked over a long time period. To align the images of the same imaging instrument with high precision, we applied the Fourier cross-correlation technique implemented in the SSW routine “tr_get_disp.pro” to the image sequences. To co-align the images from different imaging instruments, the XRT-images, TRACE-images, and the SOT-chromosphere-images were shifted to match their emission features with the magnetic features in the SOT-magnetograms.

Maps of the Doppler-shift of various emission lines were obtained from the rasters of EIS, which scanned across an area from west to east between 01:12:16 and 02:08:57 UT. The spectral center of the line profile was at every spatial pixel derived by using the centroid method (Damasch et al. 1999). Artificial effects of slit tilt and the orbital variation in the spatial distribution of the spectral center were removed before deriving the Doppler-shift distribution. The orbital variation is represented by a quasi-periodic variation in the line centroid position, which is caused by the thermal drift in EIS instrument during an orbit. The orbital variation in the Fe XII line is used to correct that of the He II line. We assume the mean spectral center, inferred by averaging over the whole map of the spectral center (for each pixel) of an emission line, to be the rest wavelength of that emission line. Finally, calibrated Doppler-shift maps of the emission lines were thus obtained. The EIS images of intensity and Doppler-shift were co-aligned with the TRACE-images. For simplicity, we did not rotate the slit-positions as recorded by EIS at different times to the same reference time.

3. Analysis results

3.1. Properties of the recurrent intermittent outflows

In Fig 1a, we show the magnetic field lines that were obtained by extrapolation from the target AR by using the PFSS (potential field source surface) package available in SSW. Green lines represent open field lines assuming a source surface at $2.5 R_{\odot}$. Figures 1b and c are close-ups of the active region. The elongated coronal emission structures, referred to as strands for short hereafter, are indicated by the dashed rectangles. We note that the source surface height of $2.5 R_s$ is only an assumption, which could be set to other values. If we increase or decrease the height of the source surface, the open flux extrapolated from the edge of AR will decrease or increase, correspondingly. However, the choice of source surface height does not significantly affect our conclusion that there are some open magnetic fluxes extending from the AR edge into the interplanetary space. When seen in X-rays the strands appear more diffusive, while the Fe IX/X-emitting strands have a clear fan-like shape. These differences in appearance may be partially caused by spatial resolution of TRACE ($0.5''/\text{pixel}$) being higher than that of XRT ($1''/\text{pixel}$). In this target AR, some micro-flares and plasma ejections at the closed loops were found to be generated by coronal magnetic reconnection with photospheric flux convergence as the driver (He et al. 2010).

Figure 2 shows the temporal variations in intensities along these three strand structures. The intensity at every height of the cut is obtained by integration across the cut. The top three panels of Fig. 2 represent the three cuts in the XRT images. Their counterparts from TRACE are illustrated in the bottom

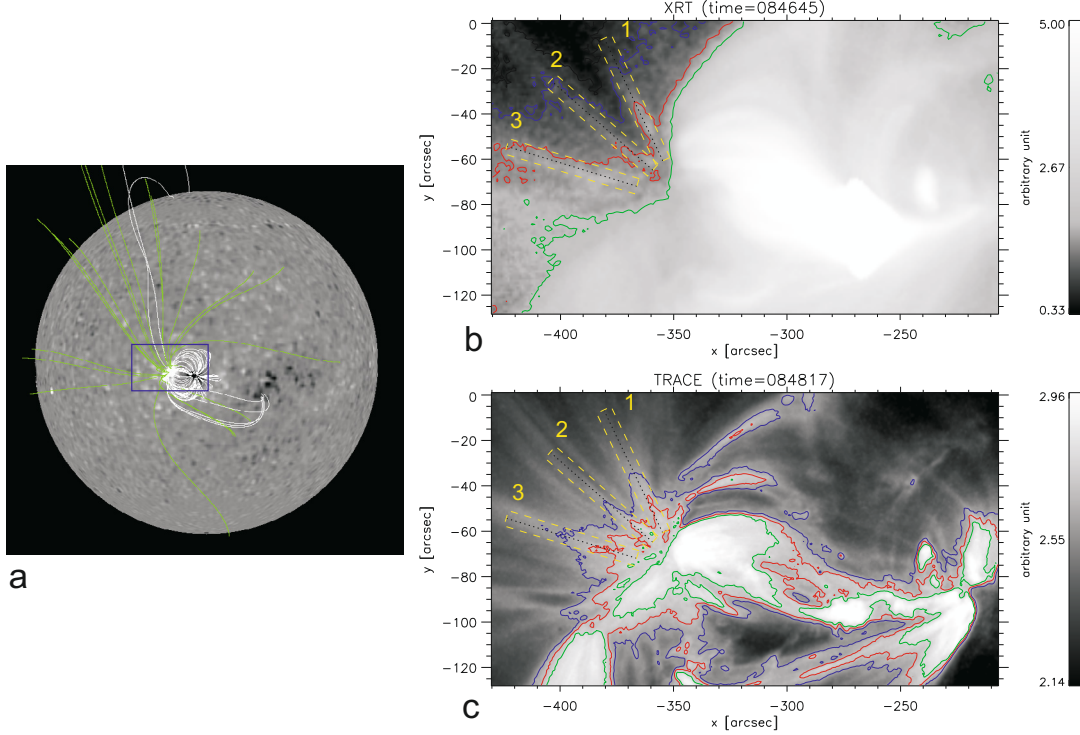


Fig. 1. **a)** Full disk magnetogram taken on February 21, 2007. The magnetic field configuration around the AR is obtained by magnetic field extrapolation using the PFSS method from the SSW package. Green lines represent open field lines passing through the source surface at $2.5 R_{\odot}$. White lines denote closed field lines. **b)** The edge of the solar AR as observed by XRT with the Al-mesh filter at 08:46:45 UT. Three yellow slit-cuts are placed along three coronal strand structures. Three different intensity levels (0.93, 1.40, and 1.80) are outlined in blue, red, and green, respectively. **c)** The edge of the solar AR observed by TRACE in Fe IX/x (171 Å) at 08:48:17 UT. The yellow slits are placed at the same positions as those in the panel **b)**. The colored contours in blue, red, and green represent the intensity levels with 2.59, 2.68, and 2.76, respectively.

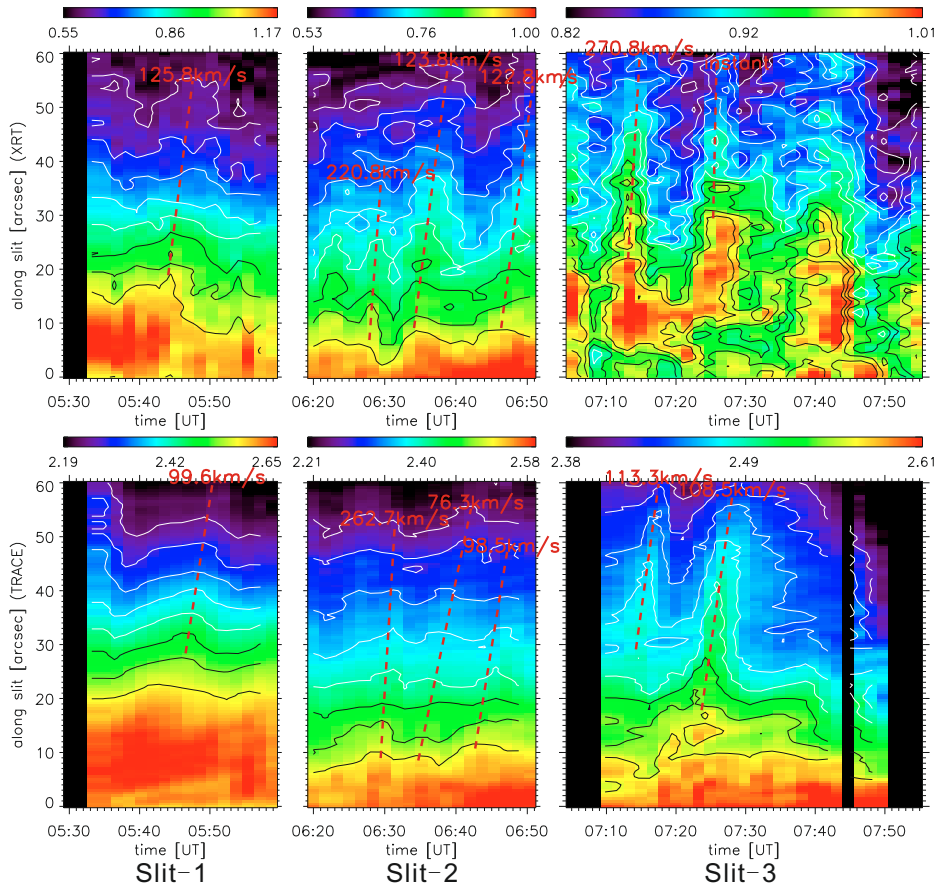


Fig. 2. Height-time diagrams of the intensity changes in slits 1 to 3 (from left to right) observed by XRT (top) and TRACE (bottom). The intensity levels for the contours in white and black from top to bottom in each panel are at 10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80% of the intensity range. The red dashed lines are drawn along the propagation paths of intensity enhancements to indicate the intermittent outflow events. The flow speeds are marked for every outflow event. A flow speed exceeding the observational resolution is replaced by the term “instant”. The black stripes represent the data gaps.

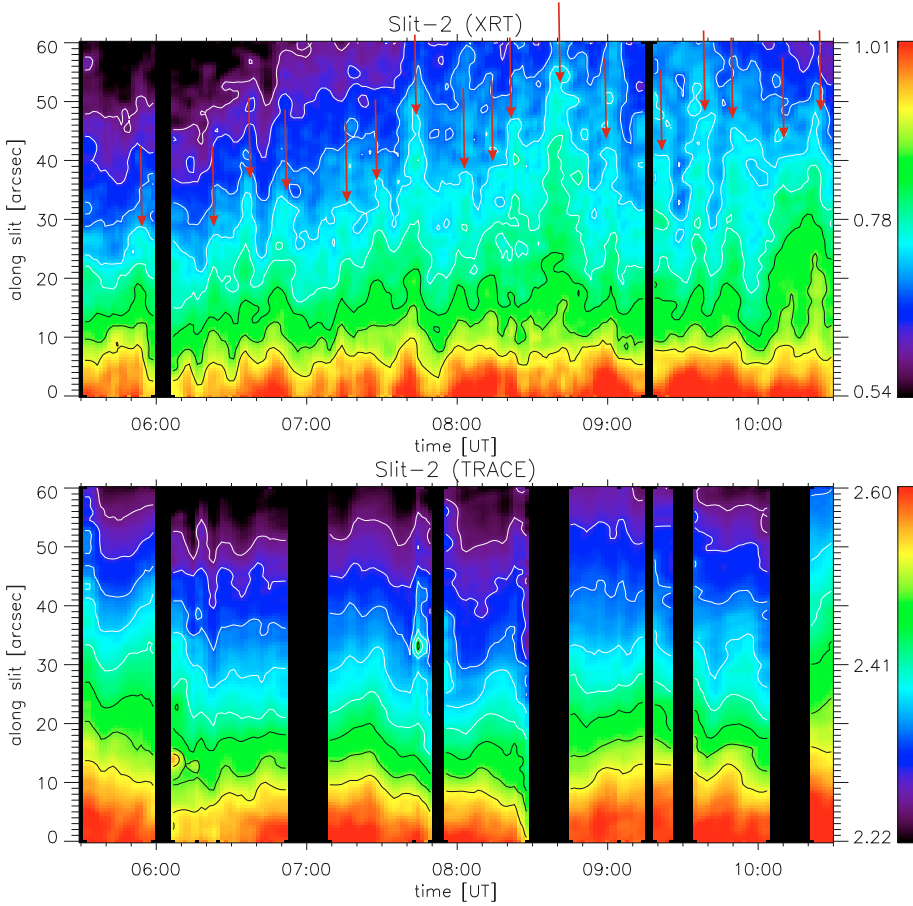


Fig. 3. Height-time diagrams of the intensity changes in slit-2 observed by XRT (*top*) and TRACE (*bottom*) in a period as long as 5 h. The intensity levels for the contours in white and black from *top to bottom* in each panel are at 10%, 20%, 30%, 40%, 50%, 60%, 70%, and 80% of the intensity range. Red arrows indicate the occurrence of intermittent outflow events. The black stripes represent data gaps.

three panels. To highlight the intensity variations at various distances, the rainbow color-table is adopted. Therefore, a subtraction of the background intensities is not required. Several intensity levels are outlined in Fig. 2 by contour lines, which mark the motions of the intensity levels. The propagation of the intensity enhancements can thus be identified. They are denoted by red dashed lines in Fig. 2, and their travelling speeds, given by the slopes of the dashed line, are indicated. This type of intensity-enhancement propagation seen in soft X-rays suggests a relation to plasma outflow, since steady Doppler blue-shifts of the Fe XII line were discovered at the roots of these strands (Harra et al. 2008). From Fig. 2, we can see that the outflow events recorded by XRT generally have their counterparts in TRACE observations. However, the outflow speeds of the soft-X-ray-emitting plasma component are slightly higher than those of the Fe IX/X-emitting plasma component.

The outflow speeds as estimated in Fig. 2 correspond to projected-speed components, and sometimes reach more than 200 km s^{-1} , which exceeds the local coronal sound speed ($C_s = \sqrt{2\gamma k_B T / m_p} \sim 203 \text{ km s}^{-1}$ for an assumed T of $1.5 \times 10^6 \text{ K}$). To estimate the true outflow speed, we may assume that the plasma flows outward along the magnetic field line, and therefore multiply the projected speed component by B/B_{LOS} , the ratio of the magnetic field to its line-of-sight (LOS) component, which in this case is about 1.8. As a result, we find that most outflow speeds do exceed the coronal sound speed. This supersonic property reconfirms the solar wind nature of the plasma flow related to the intensity-enhancement propagation. The rapid acceleration of the nascent slow solar wind at low altitudes below 60 Mm has not yet been modelled in numerical simulations (e.g., Cranmer et al. 2007; Chen & Hu 2001), which so far involved

mainly the slow solar wind originating in the boundary of a CH or helmet streamer. Other high-speed phenomena, i.e., explosive events and plasma jets, are often related to magnetic reconnection (Innes et al. 1997).

In Fig. 3, we present the intermittent outflows observed within 5 h by XRT and TRACE. The red arrows in the top panel indicate the occurrences of intermittent outflows. They are found to occur 17 times within 5 h, which means that an intermittent solar wind flow erupts outward in an individual plume about once every 20 min. It can be seen that the flow outbursts differ from event to event. They occasionally seem to be stronger, showing an obvious intensity enhancement that propagates to greater heights, while in other cases they appear to be weaker.

3.2. Chromospheric activities in the source region

We present the chromospheric activities, which are probably responsible for the intermittent coronal outflows. Figure 4a shows the corresponding chromosphere image in Ca II H line. We can see that the chromosphere beneath the edge of a coronal AR is a bright plage. The region outside this plage is occupied by numerous obvious reverse granules (Rutten et al. 2004). We select a sub-area (red dashed rectangle in Fig. 4a) where outflows visible in slit-2 originate, to investigate the possible associated chromospheric activity there. The time variation in the mean intensity of the sub-area is plotted in Fig. 4b. The corresponding power-spectrum-density (PSD) is calculated by using the wavelet method, which is similar to the method used by Bale et al. (2005) to analyze the PSD of electromagnetic fields in the solar wind. One peak of the PSD profile at a period of about

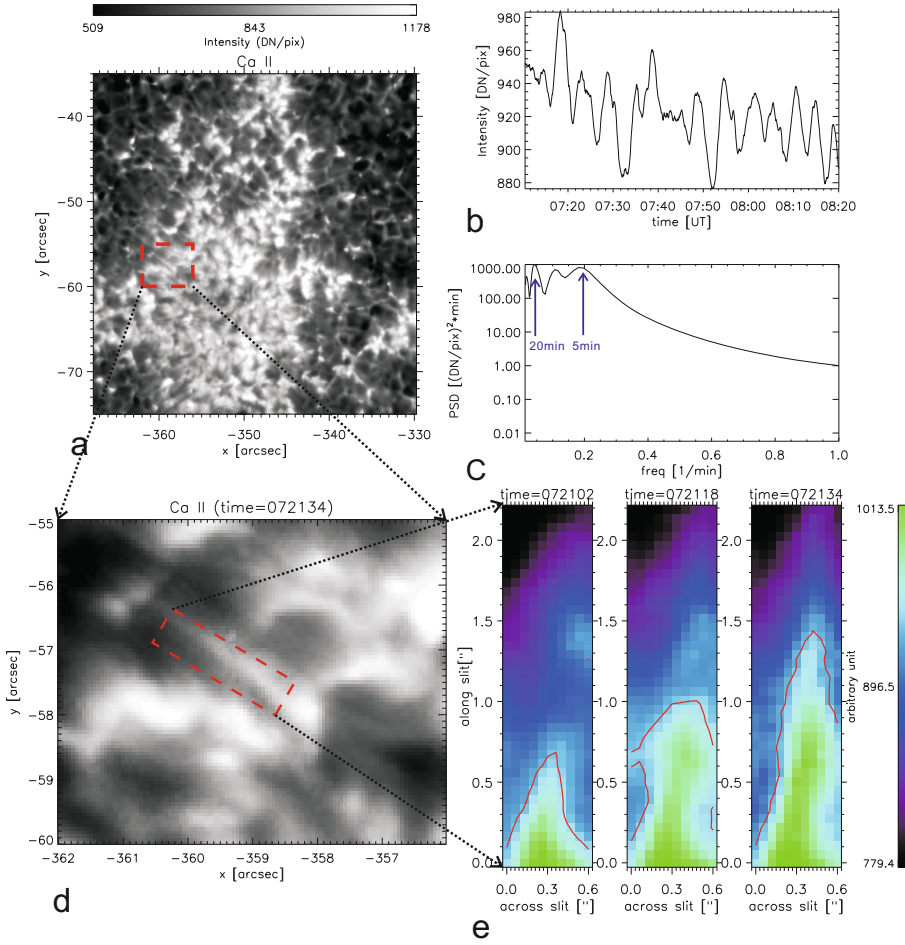


Fig. 4. **a)** Chromospheric image at the root of the coronal outflows observed by SOT in Ca II. The red dashed rectangle outlines a sub-area in which the intensity variation is to be investigated, as shown in the two right panels. **b)** Temporal evolution of the mean intensity in the sub-area. **c)** Power-Spectrum-Density (PSD) of the intensity profile as obtained from wavelet analysis. **d)** A chromospheric spicule-like jet outlined by a red dashed tilt rectangle in the sub-area. **e)** A sequence of snapshots of this chromospheric jet launch. Red contours are marked at the intensity-front level of 933.

5 min is clearly shown in Fig. 4c. This result supports the conclusion by De Pontieu et al. (2004) that the p-mode energy may leak to the chromosphere via the inclined field line, and thus stimulate 5 min activities in the chromosphere. Another obvious peak of PSD profile is located at the period around 20 min, which seems to be caused by recurrent intensity enhancements associated with chromospheric jets. The intensity variations in other sub-areas at the source region exhibit similar PSD profiles.

One case of a chromospheric jet launch in that sub-area is shown in Figs. 4d and e. We estimate the jet speed component in the projection plane to be 17 km s^{-1} , based on the motion of the intensity front (red contour in Fig. 4e). The true speed of the jet plasma after correcting the projection effect is estimated to be 25 km s^{-1} . Three jets broke out in this sub-area over about one hour. These chromospheric jets were oriented in the projection plane in a similar direction as the coronal outflows outlined by slit-2. Moreover, the chromospheric jets took place at a similar frequency (three times per hour) as the intermittent coronal outflow in the strand structure. Thus, we infer that the intermittent coronal outflow might be caused by the chromospheric jet. In previous studies, chromospheric spicule-like jets were often reported near the solar limb, e.g., chromospheric anemone jets (Shibata et al. 2007) and the type-II spicule with jet signature (De Pontieu et al. 2007). Here, we find that chromospheric jets occur on the solar disk in the possible solar wind source region. The driver of the chromospheric jet might be attributed to magnetic reconnection in the chromosphere (Shibata et al. 2007; De Pontieu et al. 2007) or a shock wave leaking from the photosphere along the inclined magnetic field lines (Hansteen et al. 2006).

3.3. Doppler blue-shifts from the chromosphere to the corona

The intensities and Doppler-shifts of the chromospheric line (He II 256.32 Å) and the coronal line (Fe XII 195.12 Å) are illustrated in Fig. 5. The formation temperatures of these two emission lines are 5×10^4 and 1.3×10^6 K, respectively. The north part of the edge of the AR is outside the field of view (FOV) of the EIS raster. We can only see the south part of the edge in the EIS images. The absolute rest wavelengths of the above lines are unknown, but as an alternative we can assume the spectral-center position averaged over the FOV to be the rest wavelength. The Doppler-shift distribution is consequently derived. The black contours in Fig. 5e outline the blue-shifts of Fe XII with a line-of-sight (LOS) outflow velocity of more than 10 km s^{-1} . Blue-shifts of He II also appear at the edge of the AR (see Fig. 5b), which shows a pattern similar to that of Fe XII. Apart from at the edge of the AR, we observe the He II blue-shift at another part of the AR, which may represent upflowing material confined in closed loops rather than outflowing mass into the solar wind. The blue-shifts of He II, and the chromospheric jets observed by SOT in Ca II, imply that the nascent solar wind outflows might already have formed at the height of the chromosphere. We note that the He II line is also defined as a line emitting from the lower transition region (Imada et al. 2007). There are blends with Si X (256.37 Å), Fe XII (256.41 Å) and Fe XIII (256.42 Å) lines in the red wing of the He II spectrum profile. In the quiet Sun and active regions of the solar disk, these coronal line blends contribute a little (less than 20%) to the spectrum profile, although they considerably affect the He II spectrum profile above the solar limb, where coronal lines generally dominate

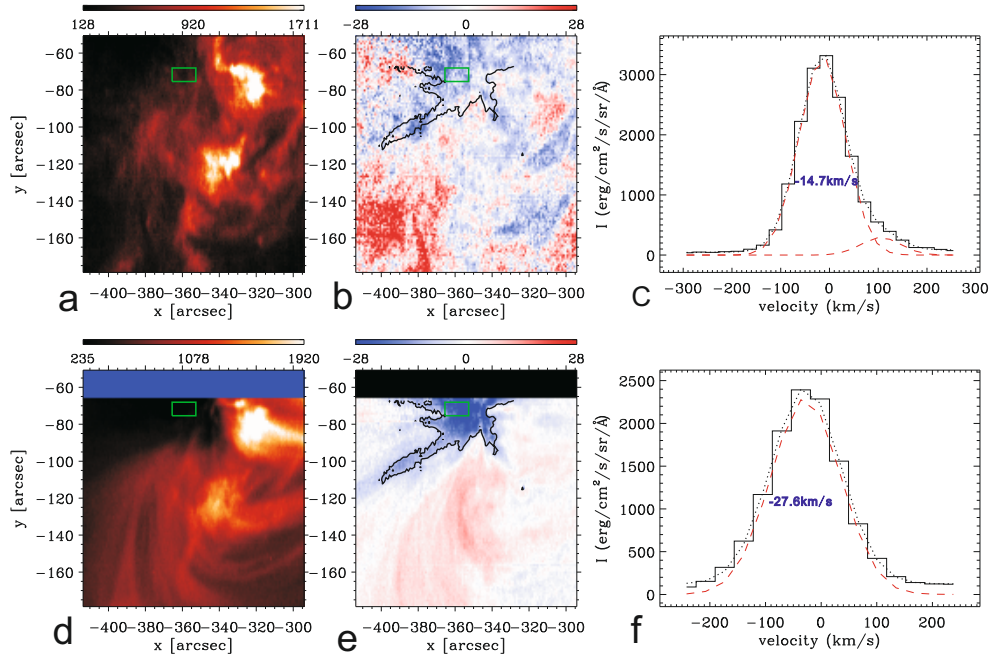


Fig. 5. *Top:* distribution of the He II intensities **a**) and Doppler shifts **b**), as well as the spectrum profile of He II **c**) in the sub-area outlined by a green rectangle. *Bottom:* distribution of the Fe XII intensities **d**) and Doppler shifts **e**), as well as the spectrum profile of Fe XII **f**) in the sub-area outlined by a green rectangle. The black contours in **b**, **e**) outline the area with blue-shifts of Fe XII larger than 10 km s^{-1} . The black dotted lines in **c**, **f**) show the composite fits of the spectrum profiles, and the red dashed lines represent the individual Gaussian components of the fit.

(Young et al. 2007). The He II spectrum profile with coronal line blends in our case is plotted in Fig. 5c. We fit this spectrum profile with a double-Gaussian function, of which the major Gaussian component with a large amplitude represents the He II emission and the minor Gaussian component with a relatively far smaller ($<10\%$) amplitude represents the blends. Thus, we infer that the blends contribute little to the He II spectrum profile in our case. From Figs. 5c and f, we find that the Doppler blue-shifts of these emission lines increase their value in proportion to the formation temperatures. This dependence of blue-shift on temperature is consistent with similar relations discovered by Imada et al. (2007) in one plage region near an AR, and by Del Zanna (2008) at the boundary of AR loops.

3.4. Connection between solar-wind source region and interplanetary stream

We now investigate the solar-wind-stream counterpart of the coronal outflows near the solar AR in the interplanetary space. The synoptic chart of the magnetic field component B_{LOS} measured by NSO/KP for Carrington Rotation (CR) 2053 is shown as the black-and-white background in Fig. 6a. Coronal holes with positive or negative magnetic polarity are outlined in blue or red contours in Fig. 6a, which is based on a synoptic map of the He I (1083 nm) line from NSO/KP. Magnetic field lines, which almost reach the ecliptic plane section facing the Earth at the altitude of $2.5 R_{\odot}$ are also plotted in Fig. 6a, where the blue or red lines represent, respectively, the positive or negative magnetic polarities at their solar footpoints (green solid circles in Fig. 6a). From Fig. 6a, we can approximately identify three low-latitude CHs at the Carrington longitudes of 20° , 100° , and 270° , respectively. The AR edge discussed here, which is indicated by a magenta-shaded rectangle in the figure, is located northwest of the second low-latitude CH (around the Carrington longitude of

100°) in that figure. We show below that the AR edge is probably connected to an intermediate-speed stream (indicated by the magenta dashed arrow in Fig. 6), while the second low-latitude CH may be the source of a high-speed stream (indicated by the first blue dashed arrow in Fig. 6).

The solar wind streams occurring during this Carrington rotation (CR-2053) measured by the ACE satellite are plotted in Figs. 6b and c. Three high-speed streams ($>600 \text{ km s}^{-1}$) were found to correspond to three low-latitude CHs. Moreover, the magnetic field components B_x in GSE of these three high-speed streams were inferred to be positive, negative, and negative, which are consistent with the polarities of the magnetic field lines extrapolated from the three low-latitude CHs. The extrapolation method applied here is PFSS, the same as we used in Fig. 1a. This close relationship between the CHs and the fast solar wind streams indicates the reliability of the connection analysis between the AR edge and its interplanetary counterpart, which we now describe. The AR edge rotated to the side toward the Earth around 12:00 UT on February 22. This time is probably the starting time of the solar wind stream with a speed of 400 km s^{-1} measured by ACE between February 26 and 27. This speed has an intermediate value between 300 km s^{-1} and 600 km s^{-1} . Therefore, we may suggest that the nascent outflows from the AR edge will finally evolve into the intermediate-speed solar wind streams at 1 AU, which are indicated by the magenta shaded-rectangles in Figs. 6b–g.

The plasma characteristics (i.e., temperature, number density, and flow velocity) of the intermediate-speed stream and its ambient environment are illustrated, respectively, in Figs. 6d–f. The temperature of the intermediate-speed stream is above 10^5 K , considerably higher than that of the normal slow wind and slightly lower than that of the fast wind (Schwenn & Marsch 1990). The number density is about 5 cm^{-3} , which is between the values typical of the fast and slow streams. Compared with the typical parameter profiles for the stream interface (SI) and

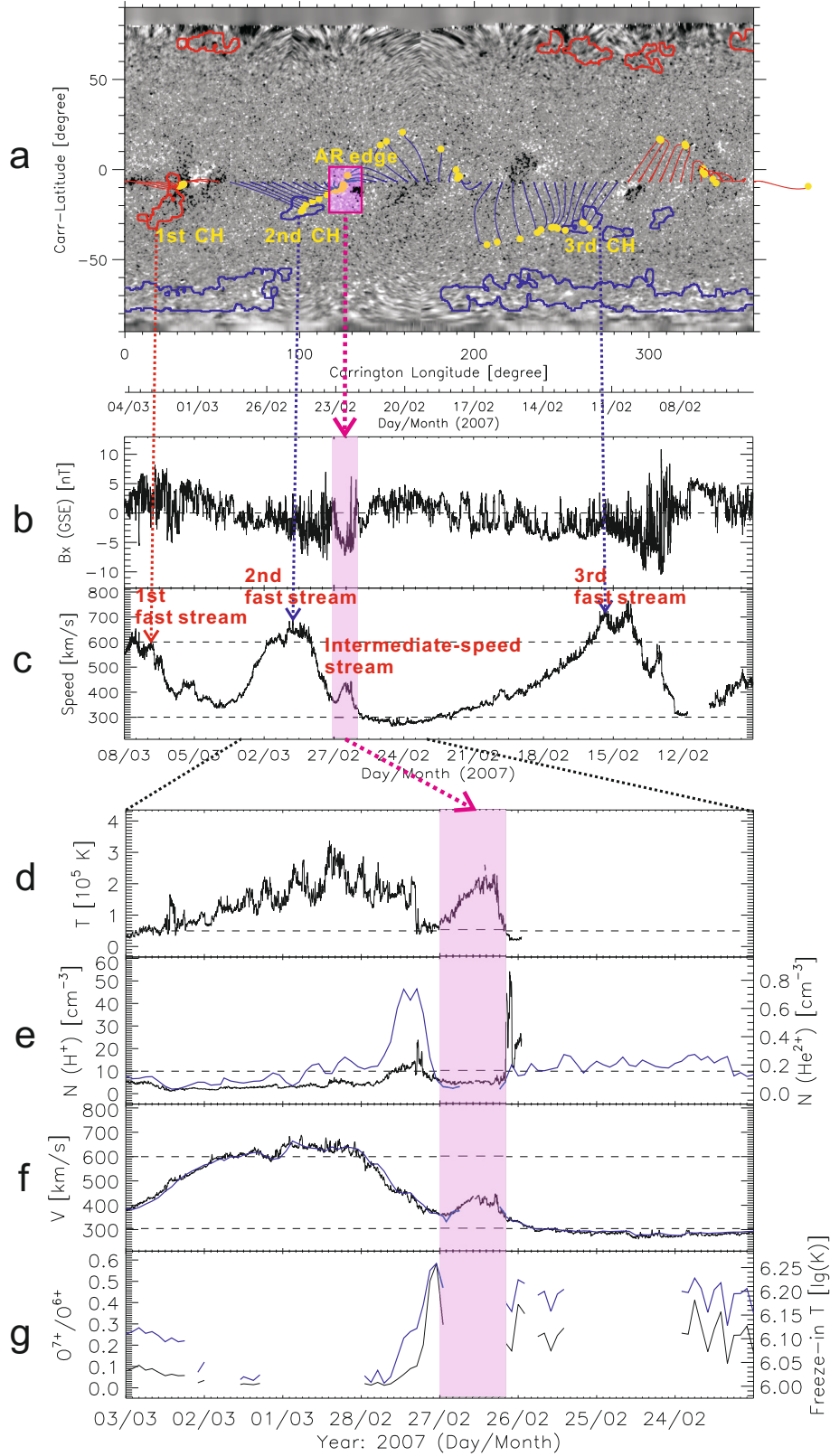


Fig. 6. **a)** The black-and-white background is a synoptic map of B_{los} for CR-2053 obtained from NSO/KP. The blue and red contours represent CHs with positive and negative magnetic polarities as derived from the He I (1083 nm) line observed at NSO/KP. The blue and red lines denote magnetic field lines with positive or negative magnetic polarity, which are extrapolated from the altitude of $2.5 R_{\odot}$ at the ecliptic section toward the Earth back to the photosphere. Their footpoints in the photosphere are denoted by yellow solid circles. The magenta-shaded rectangle outlines the edge of AR studied here. **b)** Magnetic field measured by MAG/ACE corresponding to CR-2053. The part of in-situ measurements related to the outflows from the edge of the AR is outlined by a magenta-shaded rectangle in this panel and below. **c)** Solar wind speed measured by SWEPAM/ACE corresponding to CR-2053. Panels **d–g)** display the temperature, density, speed, and the ratio O^{7+}/O^{6+} of the ACE-measured solar wind streams emanating from the edge of the studied AR and its ambient CH. The blue line in **e)** represents the He^{2+} density. The blue line in **g)** gives the freeze-in temperature as derived on the basis of ionization equilibrium.

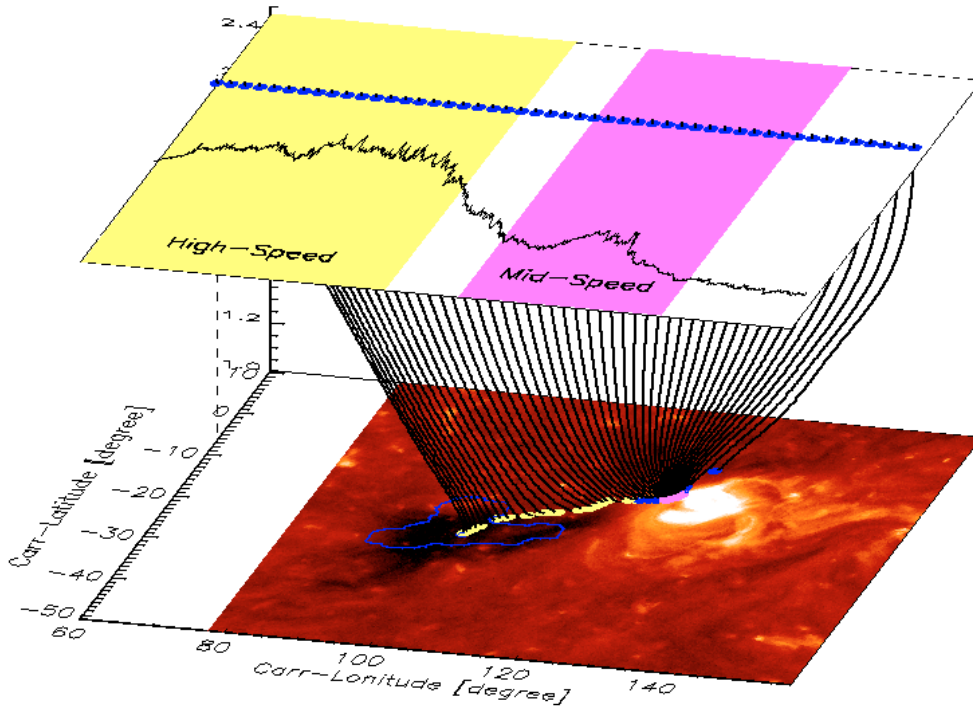


Fig. 7. Open magnetic fluxes and possible solar wind streams from the AR edge and the neighboring CH. The x -axis and y -axis represent the Carrington longitude and latitude, respectively, and the z -axis is the distance from the solar center. The XRT image is placed at an assumed distance of $1.0 R_{\odot}$ from the solar center. The blue contour on the XRT image outlines the CH detected by NSO/KP in He I (1083 nm). Magnetic field lines are obtained in the same way as in Fig. 6. The related solar-wind speed profile measured by ACE is plotted in a plane at a distance near $2.5 R_{\odot}$, the magenta and yellow shaded ranges representing intermediate-speed and high-speed streams, respectively. The blue solid circles in this plane are the intersection points between magnetic field lines and the plane. The magnetic field lines related to the intermediate-speed and high-speed streams are denoted by magenta and yellow solid circles at their footpoints, respectively.

the co-rotating interaction region (CIR) (Schwenn & Marsch 1990), we believe that this intermediate-speed stream is an independent stream rather than a result of the co-rotating interaction between low- and the high-speed stream. It is a pity that there are data gaps in time for the He^{2+} density (Fig. 6e) and the ratio $\text{O}^{7+}/\text{O}^{6+}$ (Fig. 6g) during the period of the intermediate-speed stream. The blue line in Fig. 6g represents the freeze-in temperature profile, which was derived from the $\text{O}^{7+}/\text{O}^{6+}$ ratio based on the assumption of ionization equilibrium (Geiss et al. 1995). We may speculate that the freeze-in temperature of the intermediate-speed stream is similar to that of the slow stream ($\log T = 6.25$), but higher than that of the fast stream ($\log T = 6.0$), if we fill the data gaps simply by means of linear interpolation.

The AR edge and the second low-latitude CH are not completely independent of each other. From the XRT-image in Fig. 7, we can see that the western (right) part of the CH extends to close to the AR edge. Some imbalanced magnetic fluxes from the AR edge are associated with the intermediate-speed stream. The footpoints of these magnetic field lines are indicated by the magenta solid circles in Fig. 7. Another fraction of imbalanced magnetic fluxes from the AR edge, the footpoints of which are denoted by the rightmost yellow solid circles in Fig. 7, extends into the neighboring CH, and plasma flowing along these magnetic field lines may contribute to part of the fast stream. Therefore, we suggest that the AR edge may not only be the source region of the intermediate-speed stream, but also have an impact on the outflows from the neighboring CH. The possible influence of the AR edge on the neighboring CH supports the conclusion by Habbal et al. (2008). We note that we do not implement the ballistic mapping method to obtain the speed profile at $2.5 R_{\odot}$: this is because the ballistically-mapped speed profile does not look reliable but ambiguous in our case, an individual time point possibly corresponding to multiple speed values.

4. Summary and discussion

We have investigated the properties and discussed the possible origin of the intermittent outflows from the edge of an AR. This

intermittent flow in an individual AR strand structure was found to recur about once every 20 min, and could generally be observed by both XRT and TRACE. However, the flow speed of the soft-X-ray-emitting plasma component was slightly higher than that of the Fe IX/X-emitting plasma component. The flow speed occasionally exceeded the coronal sound speed, which may be indicative of a rapid acceleration of the flow at low altitudes (<100 Mm). Since the residual magnetic fluxes at the edge of ARs often exist in the form of open field lines, plasma emanating outward from this edge is believed to contribute significantly to the nascent solar wind.

The source region of the intermittent coronal outflow in the chromosphere was found to be part of a plage. Chromospheric spicule-like jets were observed to be launched in the source region, which possibly indicates that magnetic reconnection or the propagation of a shock wave occurs there. The upflows in the chromosphere were also confirmed by Doppler blue-shifts of He II in the source region.

The interplanetary counterpart of the outflow from the edge of the AR has been identified, which is based on the consistency between the signatures in the remotely measured synoptic maps of the solar magnetic field and the time sequences of the plasma and field parameters measured in situ by ACE. Thus we found by comparison that the nascent solar wind originating at the edge of an AR evolved into an intermediate-speed solar wind stream in the interplanetary space near the Earth. This intermediate-speed stream has been found to have the following characteristics: it is hotter than the slow stream but slightly cooler than the fast one; its density is lower than the slow stream but a little higher than the fast one; its freeze-in temperature is speculated to be similar to that in a slow stream but higher than that in a fast one. Part of the residual open magnetic flux from the AR edge may also extend into the neighboring CH, and thus have an impact on the outflow from the CH by contributing some plasma to the fast solar wind stream.

Until now, there has been no theoretical or numerical model that can explain the generation of the solar wind at the edge of ARs. In previous solar wind models, the slow solar-wind streams

originate at the boundaries of CHs or in helmet streamers, and only exceed the local sound speed at a distance of more than $1 R_{\odot}$ away from the solar surface (Chen & Hu 2001). These numerical results obviously do not satisfy our observations near ARs. Therefore, it will be necessary to build a new theoretical model, which may consider chromospheric activities, e.g., magnetic reconnection or shock wave, as the possible driver to generate chromospheric jets as well as intermittent coronal outflows. The work presented here provides new empirical constraints, and our observational results will help in guiding future modelling efforts.

Acknowledgements. Hinode is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in co-operation with ESA and NSC (Norway). We would like to thank the SOT, XRT, TRACE, and the NSO/KP teams for making their data publically available on the internet. We thank the anonymous referee for his/her careful reading of the paper and for the valuable comments. The comments from the editor Dr. H. Peter are also appreciated. J.-S. He is supported by the post-doctoral fellowship program at MPS. C.-Y. Tu, L.-J. Guo, and H. Tian are supported by the National Natural Science Foundation of China under Contract Nos. 40874090, 40931055, and 40890162.

References

- Aschwanden, M. J. 2001, *ApJ*, 560, 1035
- Bale, S. D., Kellogg, P. J., Mozer, F. S., Horbury, T. S., & Reme, H. 2005, *Phys. Rev. Lett.*, 94, 215002
- Banerjee, D., O'Shea, E., & Doyle, J. G. 2000, *Sol. Phys.*, 196, 63
- Chae, J., Qiu, J., Wang, H., & Goode, P. R. 1999, *ApJ*, 513, L75
- Chen, Y., & Hu, Y. Q. 2001, *Sol. Phys.*, 199, 371
- Cranmer, S. R., van Ballegoijen, A. A., & Edgar, R. J. 2007, *ApJS*, 171, 520
- Dammasch, I. E., Wilhelm, K., Curdt, W., & Hassler, D. M. 1999, *A&A*, 346, 285
- De Pontieu, B., Erdélyi, R., & James, S. P. 2004, *Nature*, 430, 536
- De Pontieu, B., McIntosh, S., Hansteen, V. H., et al. 2007, *PASJ*, 59, 655
- Deforest, C. E., & Gurman, J. B. 1998, *ApJ*, 501, L217
- Del Zanna, G. 2008, *A&A*, 481, L49
- Doschek, G. A., Warren, H. P., Mariska, J. T., et al. 2008, *ApJ*, 686, 1362
- Esser, R., Lie-Svendsen, Ø., Janse, Å. M., & Killie, M. A. 2005, *ApJ*, 629, L61
- Geiss, J., Gloeckler, G., von Steiger, R., et al. 1995, *Science*, 268, 1033
- Habbal, S. R., Scholl, I. F., & McIntosh, S. W. 2008, *ApJ*, 683, L75
- Hackenberg, P., Marsch, E., & Mann, G. 2000, *A&A*, 360, 1139
- Hansteen, V. H., De Pontieu, B., Rouppe van der Voort, L., van Noort, M., & Carlsson, M. 2006, *ApJ*, 647, L73
- Harra, L. K., Sakao, T., Mandrini, C. H., et al. 2008, *ApJ*, 676, L147
- He, J., Marsch, E., Tu, C., & Tian, H. 2009, *ApJ*, 705, L217
- He, J., Marsch, E., Tu, C., Tian, H., & Guo, L. 2010, *A&A*, 510, A40
- He, J.-S., Tu, C.-Y., & Marsch, E. 2007, *A&A*, 468, 307
- He, J.-S., Tu, C.-Y., & Marsch, E. 2008, *Sol. Phys.*, 250, 147
- Imada, S., Hara, H., Watanabe, T., et al. 2007, *PASJ*, 59, 793
- Innes, D. E., Inhester, B., Axford, W. I., & Wilhelm, K. 1997, *Nature*, 386, 811
- Kojima, M., Fujiki, K., Ohmi, T., et al. 1999, *J. Geophys. Res.*, 104, 16993
- Liewer, P. C., Neugebauer, M., & Zurbuchen, T. 2004, *Sol. Phys.*, 223, 209
- Marsch, E. 2006, in *Proceedings of the ILWS Workshop*, ed. N. Gopalswamy, & A. Bhattacharyya, 111
- Marsch, E., & Tu, C.-Y. 1997, *Sol. Phys.*, 176, 87
- Marsch, E., Tian, H., Sun, J., Curdt, W., & Wiegmann, T. 2008, *ApJ*, 685, 1262
- Marsch, E., Wiegmann, T., & Xia, L. D. 2004, *A&A*, 428, 629
- Marsch, E., Zhou, G., He, J., & Tu, C. 2006, *A&A*, 457, 699
- Robbrecht, E., Verwichte, E., Berghmans, D., et al. 2001, *A&A*, 370, 591
- Rutten, R. J., de Wijn, A. G., & Sütterlin, P. 2004, *A&A*, 416, 333
- Sakao, T., Kano, R., Narukage, N., et al. 2007, *Science*, 318, 1585
- Schwenn, R., & Marsch, E. 1990, *Physics of the Inner Heliosphere I. Large-Scale Phenomena*, ed. E. Schwenn, & R. Marsch
- Shibata, K., Ishido, Y., Acton, L. W., et al. 1992, *PASJ*, 44, L173
- Shibata, K., Nakamura, T., Matsumoto, T., et al. 2007, *Science*, 318, 1591
- Tian, H., Marsch, E., Curdt, W., & He, J. 2009, *ApJ*, 704, 883
- Tian, H., Tu, C., Marsch, E., He, J., & Kamio, S. 2010, *ApJ*, 709, L88
- Tian, H., Tu, C.-Y., Marsch, E., He, J.-S., & Zhou, G.-Q. 2008a, *A&A*, 478, 915
- Tian, H., Xia, L., & Li, S. 2008b, *A&A*, 489, 741
- Tu, C.-Y., & Marsch, E. 1997, *Sol. Phys.*, 171, 363
- Tu, C., Zhou, C., Marsch, E., et al. 2005a, in *Solar Wind 11/SOHO 16, Connecting Sun and Heliosphere*, ed. B. Fleck, T. H. Zurbuchen, & H. Lacoste, ESA Special Publication, 592, 131
- Tu, C.-Y., Zhou, C., Marsch, E., et al. 2005b, *Science*, 308, 519
- Wang, Y.-M., Sheeley, Jr., N. R., & Nash, A. G. 1990, *Nature*, 347, 439
- Wang, Y.-M., Sheeley, N. R., Socker, D. G., Howard, R. A., & Rich, N. B. 2000, *J. Geophys. Res.*, 105, 25133
- Winebarger, A. R., DeLuca, E. E., & Golub, L. 2001, *ApJ*, 553, L81
- Xia, L. D., Marsch, E., & Curdt, W. 2003, *A&A*, 399, L5
- Yokoyama, T., & Shibata, K. 1995, *Nature*, 375, 42
- Young, P. R., Del Zanna, G., Mason, H. E., et al. 2007, *PASJ*, 59, 857
- Zhang, J., Wang, J., & Liu, Y. 2000, *A&A*, 361, 759