MEASUREMENTS OF OUTFLOW VELOCITIES IN ON-DISK PLUMES FROM EIS/HINODE OBSERVATIONS

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ABSTRACT

The contribution of plumes to the solar wind has been subject to hot debate in the past decades. The EUV Imaging Spectrometer (EIS) on board Hinode provides a unique means to deduce outflow velocities at coronal heights via direct Doppler shift measurements of coronal emission lines. Such direct Doppler shift measurements were not possible with previous spectrometers. We measure the outflow velocity at coronal heights in several on-disk long-duration plumes, which are located in coronal holes (CHs) and show significant blueshifts throughout the entire observational period. In one case, a plume is measured four hours apart. The deduced outflow velocities are consistent, suggesting that the flows are quasi-steady. Furthermore, we provide an outflow velocity profile along the plumes, finding that the velocity corrected for the line-of-sight effect can reach 10 km s\(^{-1}\) at 1.02 \(R_\odot\), 15 km s\(^{-1}\) at 1.03 \(R_\odot\), and 25 km s\(^{-1}\) at 1.05 \(R_\odot\). This clear signature of steady acceleration, combined with the fact that there is no significant blueshift at the base of plumes, provides an important constraint on plume models. At the height of 1.03 \(R_\odot\), EIS also deduced a density of \(1.3 \times 10^8\) cm\(^{-3}\), resulting in a proton flux of about \(4.2 \times 10^{10}\) cm\(^{-2}\) s\(^{-1}\) scaled to 1 AU, which is an order of magnitude higher than the proton input to a typical solar wind if a radial expansion is assumed. This suggests that CH plumes may be an important source of the solar wind.

Key words: solar wind – Sun: corona – Sun: UV radiation

Online-only material: animations, color figures

1. INTRODUCTION

Solar plumes are ray-like bright structures extending from the base of the corona into the high corona (DeForest et al. 2001b; see also Wilhelm et al. 2011 for a recent review). They are the most conspicuous structures observed during a total eclipse (Van de Hulst 1950a, 1950b). They can be observed in both visible light and EUV (Wilhelm et al. 2011 and references therein). By tracing plume structures up to 15 \(R_\odot\), DeForest et al. (1997, 2001a) have demonstrated that the structures seen in visible light and EUV are different parts of the same phenomenon. Plumes are found to be rooted mainly at mid- and high latitudes where the global magnetic fields are open into interplanetary space. Regarding magnetic fields at their footpoints, many people believe that plumes are associated with mixed-polarity magnetic features with small bipolar fields interacting with background unipolar fields (Wang & Sheeley 1995; Wang & Muglach 2008). So far, most studies on plumes are carried out in and above polar coronal holes (PCHs) thanks to the faint background that makes plumes easy to be observed. However, some efforts have also been made to study the properties of plumes at lower latitudes seen in EUV (Wang & Sheeley 1995; Del Zanna & Bromage 1999; Del Zanna et al. 2003; Wang & Muglach 2008; Tian et al. 2011), white light (Yang et al. 2011), and radio wavelengths (Woo 1996). These studies have demonstrated the existence of plumes at lower latitudes and have shown that the properties of mid- and low-latitude plumes are similar to those of polar plumes (Del Zanna et al. 2003; Wang & Muglach 2008; Tian et al. 2011; Yang et al. 2011).

Coronal holes (CHs) are well believed to be the source regions of the fast solar wind (Krieger et al. 1973; Zirker 1977; Gosling & Pizzo 1999; Hassler et al. 1999; Xia et al. 2003). Krieger et al. (1973) were the first to associate a fast stream with a coronal hole, while Zirker (1977) suggested that all coronal holes are connected to the fast solar wind. Since plumes are mainly found in CHs, their relationship with the solar wind became a significant problem. Using the photometric data obtained in the wavelength range between 171 Å and 175 Å combined with a simple, semi-empirical model of the solar wind, Walker et al. (1993) suggested that plumes are a possible source region of the solar wind. By using the Doppler Dimming technique, Gabriel et al. (2003, 2005) concluded that plumes could provide about half of the mass that the solar wind carries into interplanetary space. More recently, using high-resolution AIA/SDO observations, McIntosh et al. (2010) and Tian et al. (2011) suggested that the high-speed structures in plumes could provide mass flux to the solar wind efficiently. Nevertheless, the conclusion is still under debate. For instance, many studies showed no clear evidence that plumes could provide sufficient momentum and mass to solar wind flows (Wang 1994; Habbal et al. 1995; Wilhelm et al. 2000; Hassler et al. 1999; Giordano et al. 2000; Patsourakos & Vial 2000; Teriaca et al. 2003).

The primary reason for ruling out plumes as a solar wind source is that the calculated mass flux in plumes is lower than needed by a typical solar wind. Evidently, such a calculation requires that the electron density and flow velocity be measured in plumes. Habbal et al. (1995) calculated the electron density in both plume and inter-plume regions in a PCH using the polarized white-light observations. Combining with a two-fluid model, they obtained the velocity in plume and inter-plume regions at different altitudes and found that the velocity of the inter-plume region was faster than that of the plume region. Through analyzing the O\textsc{i} \(\lambda 10773\) spectral data recorded by SUMER/Solar and Heliospheric Observatory (SOHO), Wilhelm et al. (1998) measured the velocity in plumes below 1.2 \(R_\odot\) and found that the outflow velocity was smaller than 18 km s\(^{-1}\) after the line-of-sight (LOS) projection was taken into account. In the same study, they also measured the velocity in inter-plume regions with the Mg \textsc{ii} \(\lambda 2800\) line and found that the LOS velocity was up to 34 km s\(^{-1}\).
Therefore, they argue that the inter-plume lanes are the genuine source regions of the fast solar wind. Through analyzing two images simultaneously taken by the two EUVI telescopes on STEREO-A and STEREO-B, Feng et al. (2009) reconstructed the location and inclination of polar plumes. Then, the outflow velocity corrected for the LOS effect is as small as 10 km s\(^{-1}\) seen in O\(\text{vi}\) observed by SUMER. They concluded that the plumes are unlikely a main source of the fast solar wind when assuming a filling factor of plumes to be 0.1 in CHs (Ahmad & Withobore 1977). Tracing the dynamic features from 1.1 \(\text{R}_\odot\) to 1.3 \(\text{R}_\odot\) in white-light observations during the total eclipse, Bělík et al. (2013) obtained a propagation speed ranging from 32 km s\(^{-1}\) to 146 km s\(^{-1}\), with an average value of 67 km s\(^{-1}\) in plume structures.

The Doppler Dimming technique (Rompolt 1967) is often used to derive the outflow velocity of off-limb plumes. In order to investigate how outflow velocities change with height at altitudes below 2 \(\text{R}_\odot\), Teriaca et al. (2003) explored observations with SUMER/SOHO and UVCS/SOHO in a PCH, and from their results, they concluded that plumes are more or less static, so inter-plume regions are suggested as sources of the fast wind. In contrast, Corti et al. (1997) found that in the heliocentric range between 1.5 and 2.3 \(\text{R}_\odot\), the outflow velocity in plumes is about the same as that in inter-plume regions. Using the same method, Gabriel et al. (2003, 2005) derived an even faster outflow velocity in plumes than in inter-plume regions below 1.6 \(\text{R}_\odot\). Nevertheless, one word of caution is that the Doppler Dimming method strongly depends on empirical assumptions of the electron density and ion temperature, thus the Doppler Dimming method strongly depends on empirical assumptions of the electron density and ion temperature, thus possibly leading to different results with different assumptions (Wilhelm et al. 2011).

Obviously, measuring the Doppler shift on the disk is a more straightforward way of getting the outflow velocity in plumes. Some spectroscopic studies have been made for on-disk plumes. By analyzing the Ne\(\text{viii}\) 770 Å line observed in a north PCH with SUMER, some authors (Hassler et al. 1999; Hassler 2000; Wilhelm et al. 2000) found that the base of the plumes does not show a clear blueshift compared to other CH regions. However, the above studies are based on observations with SUMER, which has limited spectral lines at coronal temperatures, so the measured radiation is mainly emitted by the bright cores at the bottom of plumes.

In this study, we use spectroscopic observations with the EUV Imaging Spectrometer (EIS; Culhane et al. 2007) on board the Hinode satellite (Kosugi et al. 2007), which includes many coronal lines and covers a wide temperature range. It gives us an opportunity to study the Doppler velocities in the extended structure of plumes. Meanwhile, the influence of background is lower when the extended structure of plumes projects on the dark background of CHs. This offers a bigger advantage in observing plumes than SUMER does. The paper is organized as follows. In Section 2, we describe the observations and data analysis methods. The results are shown in Section 3. The significance of our results associated with the origin of the solar wind is discussed in Section 4. A conclusion is presented in Section 5.

### 2. OBSERVATION AND DATA ANALYSIS

Four data sets obtained by EIS are used in the present study. Among them, one data set was recorded in a mid-latitude region, the others were recorded in the north pole. Because we are interested in plumes that project on CHs, the data sets with a long-exposure time and a 2′′ wide slit are chosen in order to have a good signal-to-noise ratio. The details of the scanning period, observed location, size of field of view (FOV), and exposure time for the selected data sets are listed in Table 1. In Table 2, we list eight lines with formation temperatures ranging from 50,000 K to 2 million K (MK) that are used for analyzing the intensity contrast of plumes and the CH background. Among them, five lines with good signal-to-noise ratio and no obvious blends are chosen to deduce the Doppler shift. According to Young et al. (2007) and Tian et al. (2010), these lines can be well fitted by a single Gaussian. It is noteworthy that the data taken in 2007 have been used by Banerjee et al. (2009) to search for signatures of Alfvén waves and Tian et al. (2010) to describe the scenario of the nascent fast solar wind guided by expanding magnetic funnels. The difference between the study of Tian et al. (2010) and our work will be further discussed in Section 3. We also use the data from EIT on board SOHO and AIA on board SDO to identify plumes.

The EIS data are calibrated by standard procedures including dark current, flat field, removal of cosmic rays, hot and warm pixels, and radiometric calibration via the routine eis_prep.pro provided by the instrumental team. EIS has two CCDs that cover the wavelengths from 170 Å to 210 Å and 250 Å to 290 Å respectively. Images taken by the two CCDs have offsets along the slit direction and raster-scanning direction due to the arrangement of the CCDs. According to our study, an offset of 16′′ was found between the two CCDs along the slit direction, which is in agreement with the results found by Tian et al. (2010) and Démoulin et al. (2013). The procedure eis_wave_corr.pro in Solar software is used to compensate for the orbital variations...
of the EIS line centers (Kamio et al. 2010) and the slit tilt caused by tilt of slits relative to the axes of the EIS CCDs.

Wavelength calibration is an important step for obtaining precise Doppler shifts of spectral lines. Unfortunately, EIS has neither absolute wavelength calibration on board nor cold lines as reference. However, there are two methods for obtaining the absolute Doppler shift: one assumes that the LOS velocity of the off-limb plasma is zero (Peter & Judge 1999; Kamio et al. 2007), and the other assumes that the quiet-Sun (QS) region is almost quiet and can be used as a reference. The data set taken in 2007 includes both off-limb and QS observations, which provides an opportunity to verify the two methods. Because only Fe x 184.54 Å, Fe xi 195.12 Å, and Fe xii 202.04 Å have reliable signal-to-noise ratio in the off-limb data, we use them to derive the required reference wavelengths. We first obtain a spectrum by averaging all the spectra from 65" to 143" above the limb (Tian et al. 2010). By assuming that the average off-limb spectrum is zero-shifted, we then calculate the line shifts of an average spectrum of a QS region, where the Doppler velocities are found to be $-3.0 \pm 2.8$ km s$^{-1}$, $-3.3 \pm 2.8$ km s$^{-1}$, and $-3.9 \pm 2.8$ km s$^{-1}$ in Fe x 184.54 Å, Fe xi 195.12 Å, and Fe xii 202.04 Å, respectively, which are consistent with the results found by Peter & Judge (1999) and Dadashi et al. (2011). By using cospatial and nearly cotemporal SUMER and EIS data, Dadashi et al. (2011) obtained blueshifts (upward motions) between $-2$ to $-4$ km s$^{-1}$ at temperatures between 1 and 1.8 MK. Therefore, we select the line center position averaged over a QS region, where a blueshift of 3.5 km s$^{-1}$ is assumed as the reference to calculate the absolute velocities of plumes in CHs.

An error analysis is necessary but not straightforward. Three components of errors contribute to the total error of the derived Doppler velocities: (1) the fitting error $\sigma_{\text{fitting}}$, (2) the error associated with assigning an absolute speed ($-3.5$ km s$^{-1}$ in this paper) to the QS region $\sigma_{\text{abs}}$, and (3) the error associated with the unphysical noisy stripes of the derived Dopplergrams $\sigma_{\text{noise}}$. It turns out that $\sigma_{\text{fitting}}$ is the smallest among the three (varying between $0.1$ and $0.2$ km s$^{-1}$) for the spectra employed, as the input to the fitting procedure is obtained by averaging the relevant spectra over a substantial area and therefore is close to a perfect Gaussian. As for $\sigma_{\text{abs}}$, Dadashi et al. (2011) established that for spectral lines with formation temperatures between 1 and 1.8 MK, this error ranges from 2.0 to 3.0 km s$^{-1}$ (see their Table 3); here, the median value of 2.2 km s$^{-1}$ is chosen for our purposes. $\sigma_{\text{noise}}$ can be estimated by computing the standard deviation of the derived Dopplergrams over a selected area with visible vertical and/or horizontal artifacts. For data set 1, the off-limb region is chosen whereby $\sigma_{\text{noise}}$ is estimated to be 1.7 km s$^{-1}$. However, for data sets 2, 3, and 4, the Dopplergrams are not as well organized as the one for data set 1 (compare Figures 5(b), 7(a2), and 7(b2) with Figure 3(d2)): some horizontal and vertical stripes show up in, e.g., the middle part in the lower half of Figures 5(b) and 7(b2); their origin is likely to be unphysical. Therefore, we compute $\sigma_{\text{noise}}$ in the regions where these artifacts are most evident in order not to underestimate this error, finding that $\sigma_{\text{noise}}$ reads 1.8 (2.1, 3.3) km s$^{-1}$ in data set 2 (3, 4). We then evaluate the desired total error $\sigma$ according to $\sigma = \sqrt{\sigma_{\text{fitting}}^2 + \sigma_{\text{abs}}^2 + \sigma_{\text{noise}}^2}$, the results being 2.8, 2.8, 3.0, and 4.0 km s$^{-1}$ for data sets 1 to 4, respectively.

The identification of plumes in on-disk images is not straightforward. To make plumes easier to identify, a method called Multi-scale Gaussian Normalization (MGN; Morgan & Druckmüller 2014) is applied. This method helps reveal fine scales without the loss of larger-scale information.

3. RESULTS

In Figure 1, we show the intensity map (middle panel) derived from the EIS raster scan in Fe xii 202.04 Å on 2007 October 10. The left panel shows the EIT 195 Å image with EIS field of view overlapped (vertical dotted lines). The middle panel shows the intensity map recorded by EIS in Fe xii 202.04 Å, and the right panel shows the processed image of the intensity map of EIS. The white contour lines outline the boundary of the CH, and the small region marked by the dotted line rectangle represents the typical dark region of the CH. The three tilted green full lines represent the center of the plume structures, which are better seen in the processed image (right panel), and the three full line rectangles in each plume represent the plume structure from bottom to top.

(An animation and a color version of this figure are available in the online journal.)
October 10, together with the corresponding EIT 195 Å image (left panel) with a larger FOV and processed image of the intensity map using the MGN method. As previous studies have demonstrated, plumes are identified as faint and diffuse blobs of an emission-enhanced structure with a brighter core seen in EUV on the disk (Wang & Mughach 2008). Accordingly, we may identify a number of plumes in this data set. Among them, three plumes outlined by the green solid lines (labeled PL1, PL2, and PL3) have clearly extended structures in the EIS FOV by an inspection of the corresponding processed image. The three plumes are extending to heights of around 80–100 arcsec, which are further divided into three sub-regions as bottom, middle, and top segments marked by the white rectangles for further analysis. Please note that plumes are not clearly seen in the EIT image, perhaps due to the lower sensitivity of EIT relative to EIS. Using the same procedures, we also identify and select three plumes in the other three data sets for analysis.

In CH plumes, the measured emission mainly comprises two components: the plumes themselves and the CH background. In order to estimate their specific contribution, here we define a parameter called the relative radiation intensity ($RRI = \text{intensity of selected region}/\text{mean QS intensity}$). $RRI$ represents the intensity ratio of a selected region and the mean QS region. Fortunately, the EIS FOVs cover QS regions in every event.

In Figure 2, we display the $RRI$ parameter of three plumes measured in the spectral lines of interest recorded on 2007 October 10. For comparison, the $RRI$ measurement of a typical dark region as seen in hot coronal lines in the CH is also presented. From Figure 2, one finds that the intensity of He II is generally weaker in the entire CH region including plumes than in the QS region, which is consistent with the previous EIT observations. For the dark CH region, the $RRI$ has a value larger than one in both Fe viii and Si xii lines with formation temperatures below 1 MK. This may be caused by the existence of the underlying bright network structures (also see Figure 3). The $RRI$ decreases quickly to 0.2 in Fe x. This is a typical result observed previously by SUMER (Xia 2003). However, for the coronal lines whose formation temperatures exceed 1 MK, the $RRIs$ of the dark CH region are all less than 0.1 and nearly constant (0.09, 0.08, 0.08 in Fe xi 195.12 Å, Fe xii 202.04 Å, and Fe xv 284.16 Å, respectively). This is very likely caused by the stray light and the reason why we can only obtain smaller blueshifts from these three lines in the dark region, which are comparable with those obtained in the QS region (see further discussion below).

For plumes, the $RRI$ reaches maximum in the extended structure for Fe viii and Si xii lines, which can be larger or smaller than one. These lines seem to be mainly emitted by the network structures underlying the extended structure of plumes. Nevertheless, the $RRI$ reaches a minimum for the Fe xii and Fe xiii lines and then increases again with formation temperature. Moreover, line intensities of Fe xii, Fe xiii, and Fe xv are much stronger than those of the CH background, as shown in Figure 2. Quantitatively, this may be illustrated by examining the specific $RRI$ values. Take the plume PL3 (see Figure 1, middle panel), the weakest in emission among the three plumes, for instance. For its top segment, the $RRI$ reads 0.26 in Fe xii, 0.30 in Fe xiii, and 0.34 in Fe xv. As a comparison, the background coronal hole corresponds to $RRI$ values of 0.09, 0.08, and 0.08 for the three passbands, respectively. Consequently, the contribution of the plume plasma to the overall emission can be estimated to be 65% in Fe xii, 73% in Fe xiii, and 76% in Fe xv. Given that the top segments are subject to a stronger contamination from the emission from the background coronal hole and that the plume PL3 suffers from the strongest contamination among the three plumes, we then deduce that in Fe xii (Fe xiii, Fe xv), at least 65% (73%, 76%) of the emission comes from the plume plasma itself. Actually, the derived relative contribution is consistent with those obtained by Tian et al. (2011).

Given that the plumes were deduced to be less hot than inter-plume regions (DeForest et al. 1997; Hassler et al. 1997; Banerjee et al. 2000), one may question why they emit in a line as hot as Fe xv as well. Raouafi et al. (2008) find plumes are associated with hot and transit X-ray jets, and the lifetimes of those jets range from minutes to a few tens of minutes. It then follows that the plumes we examine may be also associated with X-ray-emitting, hot structures as well. However, a close examination indicates that the main structures of plumes are almost quasi-steady. The plumes in data sets 2–4 have lifespans exceeding four hours, and their morphology remains stable in the time interval we examined (see the AIA movies and running difference movies: movie20100904, movie20100904diff, movie20110111, and movie20110111diff in the online journal). In the AIA movies (especially for data set 20110111), like Raouafi et al. (2008) found, there are many small transient structures at the base of plumes. Those explosive events are smaller in size (only several arcsecs) and weaker in intensity (the intensity changes by no more than 10%) compared to quasi-steady plume structures. For comparison, there is a classic jet in AIA movie20100904 ($t = 00:10–00:25$, $x = 75\prime\prime$, $y = 900\prime\prime$) for which the intensity increased by 35% in the 171 band and by 50% in the 193 band when the jet erupts. We suspect that the major plume plasmas can be supplied by those small transient events. As for the plumes in data set 1
acquired in 2007, the EIT 195 movie suggests that they are stable and not associated with big explosive events. One then naturally asks whether stable plumes also emit in hot lines. Actually, DeForest et al. (1997) also noticed that plumes are seen not only in EIT 171 movie and EIT 195 images but also in the Fe xv 284 band. One possibility is that although the temperature of plumes is lower than in inter-plume regions, the plumes themselves may contribute to a significant fraction of the corresponding emission due to their considerably higher densities than the surrounding coronal hole plasmas. Another possibility that cannot be ruled out is that the plume structures are composed of hot sub-resolution transients. Not resolved adequately in current observations, these transients may make the plume structures appear quasi-stable.

The intensity and Dopplergram maps derived from the Fe viii, Si vii, Fe x, Fe xi, and Fe xii lines are displayed in Figure 3. Figure 3 brings to our attention that the strong blueshift patches derived from hot lines of Fe x, Fe xi, and Fe xii coincide with the extended structures of the identified plumes. In contrast, this coincidence is not clear in cooler lines of Fe viii and Si vii, where the intensity and Dopper-shift patterns reflect mainly local network structures but not plumes. As we have mentioned, there are smaller blueshifts in the dark region of the CH, which is contourd by white lines in Figure 1 (middle panel) and red lines in Figure 3. The Doppler shift is about 2.4 km s⁻¹ in Fe xii 195.12 Å and about 3.4 km s⁻¹ in Fe xii 202.04 Å, respectively, which is comparable with the QS region. Combining with the fact that in the region where plume structure project on the CH background the radiation is mainly from plume structures for those lines with formation temperatures in excess of 1 MK, we can draw an important conclusion that the Doppler shift in the region where plume structures project on the CH reflects the outflow in plume structures.

The above analysis has further demonstrated our identification of the extended structure of plumes, which differs from the explanation of Tian et al. (2010), where they interpreted the blueshift patches in Figure 3 as evidence of the nascent fast solar wind originating from the underlying magnetic networks. In a later paper, Tian et al. (2011) have also clarified that in this data set, the blueshift patches in the CH are mainly contaminated by the plumes rooted at the boundary of the PCH (see Figure 8 in their paper).

Figure 3 shows the outflow velocity along the plumes derived from the Fe viii, Si vii, Fe x, Fe xi, and Fe xii lines. At first glance, it is a little strange that the Doppler shifts seen in the very hot lines are much different from those in colder lines at the same height. Then, which ones reflect the real Doppler shifts of plume structures? Here, we argue that the Doppler shifts of the hottest lines, whose formation temperatures exceed 1 MK, reflect more faithfully the real outflow in plumes. As shown in Figures 3(a1) and 3(b1), the plume structures are clear in Fe xii 195.12 Å and Fe xii 202.04 Å and coincide with strong blueshift patches derived from these two lines. (A color version of this figure is available in the online journal.)

Figure 4 shows the outflow velocity along the plumes derived from the Fe viii, Si vii, Fe x, Fe xi, and Fe xii lines. At first glance, it is a little strange that the Doppler shifts seen in the very hot lines are much different from those in colder lines at the same height. Then, which ones reflect the real Doppler shifts of plume structures? Here, we argue that the Doppler shifts of the hottest lines, whose formation temperatures exceed 1 MK, reflect more faithfully the real outflow in plumes. As shown in Figures 3(a1) and 3(b1), the plume structures are almost invisible in the lines of Fe viii and Si vii, which means that the emission from the CH background dominates in these cool lines. This may be further corroborated by Figures 3(a2) and 3(b2), where the Dopplergrams are shown. In contrast to the Doppler shift features in hot lines (Figures 3(c2)–(e2)), the Doppler features are not organized in linear shapes as seen in the intensity diagrams. In practice, we derive our outflow speeds for
plumes using only the Fe\textsuperscript{XIII} line. The reason we do not use the hottest line, Fe\textsuperscript{XV}, is that the spectral shape is not as good as the Fe\textsuperscript{XIII} line. In this way, we can draw a further conclusion that Doppler shifts increase with height in the extended structure of plumes. Furthermore, assuming that the plumes are extending radially, one can deduce the outflow velocity of the plume plasma by correcting the latitude/LOS effect of the plumes. For plumes of the 2007 October 10 data set, the latitude of the plumes is about 60 degrees. The outflow velocity derived from the hottest line increases with height in the plumes and reads about $10 \pm 5 \text{ km s}^{-1}$ at $1.02 R_\odot$, $15 \pm 5.6 \text{ km s}^{-1}$ at $1.03 R_\odot$, and $25 \pm 5.6 \text{ km s}^{-1}$ at $1.05 R_\odot$.

If a plume is observed near the equator and its orientation is nearly parallel to the local radial direction, it will allow us to derive its outflow velocity directly from Doppler shifts with a less strong projection effect. Fortunately, we observed a low-latitude plume in the data set of 2011 January 11 as shown in Figure 5. The plume (marked by the ellipse) is located at the boundary of a large low-latitude CH. Although it is not very clearly seen in the EIS Fe\textsuperscript{XII} 195.12 Å intensity map, it can be easily identified in the AIA 171 Å movie. The Doppler shifts of the plume structure and CH region (marked by the rectangle) are shown in Figure 6. Green, blue, and red curves represent the Doppler shifts of QS, CH, and plume regions, respectively. We find the Doppler shift of plume structure is larger than $20 \text{ km s}^{-1}$ in the coronal line Fe\textsuperscript{XII} 195.12 Å, which is consistent with the corrected velocity derived from the 2007 October 10 event.

A question may arise as to whether these blueshift patches are quasi-steady outflows or velocity patterns associated with transient events. This is necessary given that DeForest et al. (2001a) and Raouafi et al. (2008) have shown that plumes appear to be recurrent and bursty. To address this question, we...
follow a plume imaged by four hours apart on 2010 September 4, which are shown in Figure 7. The top panels show the intensity and Dopplergram observed from 18:30 to 22:02, and the bottom panels are for the measurements between 22:04 and 01:36 the following day. Among several plume structures, one projected on CH and marked by the white rectangle is chosen for further analysis. The temperature dependence of the absolute Doppler shifts in the plume and CH regions is shown in Figure 8. From Figures 7 and 8, the shape of the plume and the Doppler shifts do not change substantially in the two scans. Now the question is whether the plumes may have pulsed twice. We then examined the AIA movie for the corresponding time interval (movie20100904, now supplemented to Figure 7) and found that indeed the plume persisted for more than seven hours during these two EIS scans. From this, we conclude that the blueshift patches reflect a quasi-steady outflow pattern in the plume structure itself rather than being associated with big transient jets.

4. DISCUSSION

In the past decades, many studies have been carried out in search of the relationship between plumes and the solar wind (Walker et al. 1993; Wang 1994; Habbal et al. 1995; Hassler et al. 1999; Wilhelm et al. 2000; Giordano et al. 2000; Patsourakos & Vial 2000; Teriaca et al. 2003; Gabriel et al. 2003, 2005; McIntosh et al. 2010; Tian et al. 2011). One of the most important studies is the measurement of the outflow velocity in plume and inter-plume regions. The outflow velocity of off-limb plumes has been measured during the SOHO era (Wilhelm et al. 1998; Corti et al. 1997; Teriaca et al. 2003; Gabriel et al. 2003, 2005). However, these measurements lead to contradictory results. On the disk, Hassler et al. (1999), Hassler (2000), and Wilhelm et al. (2000) measured Doppler shifts at the bright footpoints of plumes and found no obvious velocity signature since SUMER has limited spectral lines at coronal temperatures. In this study, we analyzed several plumes observed by EIS on the disk. We derived their outflow velocity from hot coronal lines. In polar and low-latitude regions alike, a quasi-steady outflow is present in the plumes. The outflow velocity of plumes increases with height in plumes and is found to be about 25 km s$^{-1}$ at 0.05 $R_\odot$ above the surface. In Figure 9, we present the outflow velocity as a function of altitude measured by different authors and insert our results, shown as red crosses. This may provide further information on the velocity of the plume plasma from the solar surface out to 1.4 $R_\odot$, which should serve as an important constraint on plume models.

As mentioned in the Introduction, to estimate the possible contribution of plumes to the solar wind, we need to know the electron density to calculate the mass flux. At the height of 1.03 $R_\odot$, we also estimate the electron density by using the CHIANTI database in line pair Fe xiii 202.04 Å/Fe xiii 203.82 Å (Young et al. 2009) and obtain an electron density of 1.3 $\times$ 10$^6$ cm$^{-3}$. Assuming all the mass expanding from the plumes can travel to the Earth, it can contribute a proton flux of 4.2 $\times$ 10$^9$ cm$^{-2}$ s$^{-1}$ at 1 AU, which is an order of magnitude
higher than that of a typical fast solar wind if a radial expansion is assumed. It should be mentioned that the plumes we analyzed are mainly rooted at the boundary of CHs. The CH boundary is considered as a possible source of the slow solar wind (Wang et al. 2009; Subramanian 2010; Madjarska et al. 2012). Yet, the large mass flux that plumes can provide suggests that plumes may be an important source of the (fast and/or slow) solar wind, but they do experience substantial lateral expansion and/or mass exchange with neighboring inter-plume plasmas. 

In our study, we found that the CH regions do not show more significant blueshifts than the QS regions, which seems to contradict the consensus that CHs are the sources of the fast solar wind. The reason for this apparent contradiction is two fold. First, the radiation that EIS measured in the CHs is dominated by the stray light from the surrounding QS and active regions. Second, the solar wind may have been braked at the studied altitudes before being accelerated at higher altitudes. According to our analysis, we prefer the former interpretation. To corroborate this, we have estimated the electron density in the QS region and the dark region of the CH observed on 2007 October 10, the obtained density is about \( 2.2 \times 10^8 \) cm\(^{-3} \) and \( 3.7 \times 10^8 \) cm\(^{-3} \), respectively. However, it is almost impossible that a CH region was denser than a typical QS region. Combined with the fact that the RRI parameter is almost constant in lines with high temperatures found in Section 3, this means that the radiation from the hot coronal lines is mainly from the surrounding bright area most possibly scattered by the instrument. A further study on the CH region, especially using spectroscopic observations with a very low stray-light spectrometer, is needed to understand this contradiction.

5. CONCLUSION

We have measured the outflow velocity at coronal heights in several on-disk, long-duration plumes observed by EIS on board Hinode, which are located in CHs and show significant blueshifts throughout the entire observational period. The deduced outflow velocities are quasi-steady and can reach 10 km s\(^{-1} \) at 1.02 \( R_\odot \), 15 km s\(^{-1} \) at 1.03 \( R_\odot \), and 25 km s\(^{-1} \) at 1.05 \( R_\odot \) after being corrected for the LOS effect. This clear signature of steady acceleration combined with the fact that there is no clear blueshift at the base of plumes provides an important constraint on plume models. At the height of 1.03 \( R_\odot \), EIS also deduced a density of \( 1.3 \times 10^8 \) cm\(^{-3} \), resulting in a proton flux of \( 4.2 \times 10^9 \) cm\(^{-2} \) s\(^{-1} \) scaled to 1 AU, which is an order of magnitude higher than necessary for the proton input to a typical solar wind if a radial expansion is assumed. This suggests that plumes may be an important source of the solar wind.

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