Polar Coronal Plumes as Tornado-like Jets

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Abstract

We examine the dynamical behavior of white-light polar-plume structures in the inner corona that are observed from the ground during total solar eclipses, based on their extreme ultraviolet (EUV) hot and cool emission line counterparts observed from space. EUV observations from Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) of a sequence of rapidly varying coronal hole structures are analyzed. Evidence of events showing acceleration in the 1.25 Mk line of Fe XII at 193 Å is given. The structures along the plume show an outward velocity of about 140 km s$^{-1}$ that can be interpreted as an upward propagating wave in the 304 Å and 171 Å lines; higher speeds are seen in 193 Å (up to 1000 km s$^{-1}$). The ejection of the cold He I plasma is delayed by about 4 minutes in the lowest layer and is delayed more than 12 minutes in the highest level compared to the hot 193 Å behavior. A study of the dynamics using time-slice diagrams reveals that a large amount of fast ejected material originates from below the plume, at the footpoints. The release of plasma material appears to come from a cylinder with quasi-parallel edge-enhanced walls. After the initial phase of a longitudinal acceleration, the speed substantially reduces, and the ejecta disperse into the environment. Finally, the detailed temporal and spatial relationships between the cool and hot components were studied with simultaneous multiwavelength observations, using more AIA data. The outward-propagating perturbation of the presumably magnetic walls of polar plumes supports the suggestion that Alfvén waves propagate outwardly along these radially extended walls.

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

Supporting material: animations

1. Introduction

1.1. Coronal Holes

Coronal holes (CH) are regions of low-density plasma in the solar atmosphere associated with magnetic field lines that open up freely toward interplanetary space (Zirker 1977). During solar minimum, such holes cover both the north and the south polar caps. In more active periods, narrow CHs can also be seen at all solar latitudes, as first suggested in the late 1950s when M. Waldmeier noticed long-lived low-intensity regions in coronagraphic records made with the Fe XIV green line (e.g., Koutchmy 1977; Koutchmy & Bocchialini 1998; Wilhelm et al. 2011). Their more definite identification was done from soft X-rays disk images taken from sounding rockets and especially from the Skylab Apollo Telescope Mount (ATM) grazing incidence photographic X-ray telescope (Vaiana et al. 1973). Long-lived bright points were extensively studied over the whole quiet Sun (Golub et al. 1974; Habbal & Withbroe 1981), and transient brightenings were analyzed using the soft X-ray data from the Yohkoh mission (Koutchmy et al. 1997).

More specifically, CHs were seen to contain a large number of small, rapidly varying bright points that often coincided with the boundaries of supergranular cells that in turn may be related to the primary launching sites for the fast solar wind, and flares in bright points observed at the limb were seen to correspond to so-called surges and to eruptive ejections in H$\alpha$ (Moore et al. 1977; Koutchmy et al. 1997, 2012; DeForest & Gurman 1998).

The plasma in the transition region and in the corona is in a dynamical state where the details of the temperature minimum network rosettes (Beckers 1968; Sterling 2000; Lorrain et al. 2006; Tavabi 2018) and the magnetic field are measured, and the network patches higher up are observed in H$\alpha$ or in chromospheric lines (Baudin et al. 1996; Georgakilas et al. 2001; De Pontieu et al. 2014). The plasma flows successively along various magnetic field tubes in the form of spicules and jets, and finally along polar plumes. The coronal material extends toward the outer corona where the solar wind actually evolves but this behavior does not take into account the intermittence of the evolution. It is accepted that the fast solar wind emerges from magnetically open CHs, which are representative of a predominantly unipolar magnetic region (e.g., Koutchmy 1977; Zirker 1977; Bravo & Stewart 1996), of a rather quiet Sun; the slow solar wind originates from above the more magnetically active part of the Sun. To establish the CH origin of the fast solar wind it is necessary to find the source regions of the high-velocity solar wind stream at the surface of the Sun (Krieger et al. 1973).

1.2. Polar Plumes

Genuine polar plumes are linear, rather straight structures, seen in the extreme ultraviolet (EUV) line at 171 Å up to 1.3 $R_\odot$ and in white light during eclipses to much larger distances (see Figure 1 for a convincing correspondence). They should not be confused with the edge of streamer sheets seen in projection above the polar limbs (Bravo & Stewart 1996). In Figure 1 we illustrate the correlation between the classical white-light plumes from eclipse observations and the plumes seen in the excellent 171 Å Solar Dynamics Observatory/Atmospheric Imaging Assembly (SDO/AIA) filtergrams after using a summing of 80 consecutive images with a cadence of 12 s. Outwardly propagating fast features are visible in hot coronal
lines along the plumes, as illustrated in Figure 1. EUV 171 Å structures with white-light (W-L) structures make the ray-like features in the polar region, which are usually called polar plumes or polar jets. Furthermore, we looked at the relationship with He II 304 Å macrospicules and polar-erupting small prominence structures, as was suggested from simultaneous ground-based observation performed at the feet of the plume in the cool Hα line (Georgakilas et al. 2001). Macrospicules were broadly defined in He II 304 Å observations as long, usually pointed jets ranging in length from 5 arcsec to over 50 arcsec (Bohlin et al. 1975).

The ions in the high-speed solar wind accelerate to terminal speeds of about 800 km s⁻¹ above the CH (Wilhelm et al. 2000, 2011). This rapid acceleration cannot be explained by hydrodynamic forces (plasma gas pressure) alone. Some other form of momentum transfer, such as forces appearing in the region due to
self-excited dynamo (Lorrain et al. 2006) or other mechanisms, such as Alfvén-cyclotron resonance (Kasper 2008), must be at work. Coronal plumes, together with other dynamic structures in the solar atmosphere, such as macrospicules and X-ray jets, are potential sources of solar wind (spicules provide 100 times more mass than what is needed to fill the corona; Pneuman & Kopp 1978). Moreover, recent studies indicate that plumes are a plausible source of the fast solar wind streams (Gabriel

Figure 3. Snapshots of AIA 193, 171, and 304 Å showing the time evolution of the tornado-like phenomenon at the base of the selected jet in 304 Å and what is recorded in the coronal lines. An animation showing the temporal evolution is available online (the untwisting motion in the animation is more obvious when we manually run the animation at a higher speed than the default speed). Snapshot at 14:32 UT in 304 Å line shows the main axis of tornado with different cuts used to study the longitudinal motion.

(An animation of this figure is available.)
et al. 2005, 2009). Other investigations led to different results (e.g., Habbal et al. 1995; Wang et al. 1998; Wilhelm et al. 2000). Wang et al. (1998) reported speeds of 400–1100 km s$^{-1}$ for the outermost part of the W-L jets, whereas their centroidal velocities for the bulk of material are much lower. The contribution of polar plumes to the fast solar wind rising from the polar CH is thus still a subject of debate and controversy (e.g., Habbal 1992; Gabriel et al. 2003). More details about plumes and interplume regions were listed in the review of Wilhelm et al. (2011) and of Poletto (2015).

Del Zanna et al. (2003) found that bright points are seen near the plume footpoints only in the early phase of their formation. Wilhelm et al. (2010) found a strong association of plumes and jets from 

Hinode/X-Ray Telescope (XRT) images, and Raouafi et al. (2008) showed that X-ray jets are precursors of coronal plume formation. Studies of morphology, kinematics, dynamics, and the production mechanism of a rather small-scale tornado have been recently pursued (Wedemeyer-Bohm et al. 2012) at the photospheric granulation scale. The evolution as a function of height toward the corona of this type of event is still unknown. Kitiashvili et al. (2013) provided a realistic numerical simulation showing that due to the vortex at the foot of a plume, small jets could capture and stretch the background magnetic field, generate shocks, and push plasma to the upper atmosphere. The magnetic field captured in the vortex causes an initial perturbation and accelerates the plasma along the helical medium to produce a spontaneous-seeming ejection in the solar atmosphere (Lorran et al. 2006). A great number of observations and studies show that tornado-type eruptions (including surges) are composed of fine, long threads (Tavabi et al. 2015b; Chen et al. 2012). The AIA observations of polar CHs suggest that the region may be finely structured at arcsec scales in the width with multiple threads of both hot and cool dynamical tornadoes.

1.3. EUV Jets

X-ray jets were discovered with the X-ray telescope on board the Japanese Yohkoh mission (Shibata et al. 1992; Yokoyama & Shibata 1995). They are associated with small flares and occur above X-ray bright points (Golub et al. 1974). Moore et al. (1976, 1977) also showed that X-ray bright points could be associated with Hα macrospicules. Shibata et al. (1992) and Canfield et al. (1996) have reported that X-ray jets are observed to be associated with cool ejections or plasmoids, nearly simultaneously and in nearly the same direction.

There have been numerous studies predicting that twisting motions should be present in eruptive structures in the low corona. Radially directed linear structures seen above the limb exhibit fast ejections that reach peak velocities of 20–200 km s$^{-1}$ (Tavabi et al. 2011, 2015a; De Pontieu et al. 2014). At chromospheric heights they are called spicules, and usually they exhibit a rotational motion with several turns (Tavabi et al. 2013). However, the rotational behavior seems uncommon in X-ray jets (e.g., Filippov et al. 2009). Pariat et al. (2009) performed 3D magnetohydrodynamic (MHD) simulations of an instability taking place in a quasi-statically driven MHD system showing a jet; they found that torsional Alfvén waves with upflowing helical motion are the result of reconnection of initially twisted loops with open fields. Canfield et al. (1996) suggests that the rotational motion is
due to the redistribution of stored twists after reconnection with two loops that have different numbers of 360° turns. Patsourakos et al. (2008) reported on observations made by the twin spacecraft Solar Terrestrial Relations Observatory (STEREO) A and B in the EUV (195 Å and 171 Å) of a helical jet. This jet twists and untwists above the limb in a polar coronal hole. Moore et al. (2015) studied several cases of hot EUV jets in 193 Å line, with erupting loops that are also seen as bright emission in the relatively cool 304 Å line, and with darker components (absorption) seen in the 193 Å hotter line at the base of an eruptive tornado-like event, which is also seen in our study (see Figures 2 and 3). This schema suggests that the interacting loops at the reconnection X-null point are related to the rather cool chromospheric features with the initial plasma ejection being due to mutual interactions of highly twisted cool loops. Tornado phenomena were occasionally reported with a turn number of more than 3 full 360° turns (Shen et al. 2011). The number of turns and consequent untwisting behavior should be taken into account when interpreting the energy release and the acceleration mechanism. Panesar et al. (2013) reported tornados as dynamical, conspicuously helical magnetic structures mainly observed as a prominence activity that the tornado was dynamically associated with the expansion of the prominences helical field and its cavity.

2. Observations

The AIA on board the SDO (Pesnell et al. 2012) is an array of four telescopes that captures images of the Sun’s atmosphere out to 1.3 Rs in 10 separate EUV and UV wave bands (Title et al. 2006). The images are 4096 × 4096 with a pixel size of 0.6" in the full spatial resolution mode, with a cadence of 12 seconds on 2010 July 10 (Figure 2) that is considered here. A full day sequence was prepared by Koutchmy et al. (2012) for the analysis of events observed at the time of the total solar eclipse of 2010 to increase the signal-to-noise ratio and to improve the visibility of the images. The processing method is based on frame summing, radial filtering, and unsharp masking.

A solid line in Figure 4 indicates the position along which the jet was ejected. We confirm the association of plumes with small-scale explosions at their feet using a movie assembled from the AIA data (movie S1). Several examples of dynamical jets were found at the pole over a time interval of ∼24 H. They were seen at the base of much more extended plumes. To quantify these motions, we did three cuts along the axis of the selected jet, oriented roughly perpendicular to the axis shown in Figure 4. It is difficult to measure the radial velocity of the bulk of the plasma within the jets but, given the large number of such events now being seen in the 171 Å channel using running difference frames (Figure 5), it seems that in...
193 Å hotter line, the speed is large enough (Table 1) for the plasma to escape and to significantly contribute to the fast solar wind; the typical velocity is about 800 km s\(^{-1}\).

Time-slice diagrams (Figure 6) of the cuts clearly show the dynamical behavior of the trapped ejected plasma inside the plume. Based on this diagram, we suggest that the early phase of the plasma ejection, after a phase of circular motion inside the plumes, is followed by an evaporation phase (ejection) along the plume after the plasma emerges into the corona in an open-field environment, similar to that proposed by e.g., Wilhelm et al. (2011). An initial ascending radial velocity is shown by the green line of the time–distance diagram in Figure 7 (the result for the 304 Å line). It shows a typical value of 140 ± 10 km s\(^{-1}\) found for the ascending velocity. The rotational velocity is found of the order of 0.02 rad s\(^{-1}\) (145 ± 30 km s\(^{-1}\)); the deduced period of rotation is near 5 minutes. This rotational velocity is deduced assuming a spiral motion of identified features along what looks like a cylindrical surface. The average outflow velocity is the same for the 171 Å line and remains approximately constant during the ascent. Considering the velocity of the intensity front, for the 193 Å line velocity of 720 ± 10 we find up to more than 1000 ± 10 km s\(^{-1}\) during the ascent, which is in significant contrast with the apparent velocities observed in the cool 304 Å line (Figure 7).

In order to investigate this possible scenario of a helical motion followed by evaporative ejection, we analyzed the behavior of the cool part of our 304 Å jet in Figure 7 using the time–distance method. The most significant result is the evidence (see the right panel of the diagram of Figure 7) of the time–distance diagram following quasi-parabolic trajectories. Some returning flux is also seen, although the innermost part of the phenomenon inhibits a definite ejection. We note that a similar result was obtained (Kayshap et al. 2013) for a polar event interpreted as a macrospicule and the associated jet, without considering the coronal counterparts. In this study, we present detailed observations of a CH jet, with a cool tornado-like structure at the feet and extended in the radial direction.

3. Discussion

To reveal the importance of the mechanism causing tornado-like events, the events were simultaneously observed in a time sequence of data obtained at multiple wavelengths in order to understand their dynamical characteristics.
The first important aspect of this observation is the occurrence of jets as plasma ejections related to polar plumes. Raouafi & Stenborg (2014) also reported several jetlets (small jets) at the feet of plumes (see also white-light observations from eclipse images; Koutchmy & Stellmach 1976). Jets are highly dynamic and are seemingly one of the main energetic material sources for plumes. It was also noted that jet ejection along the preexisting plumes increases the plume brightness. Wilhelm et al. (2011) show that polar jets in the interplume region propagate along the plumes seen in the Large Angle and Heliospheric Observatory (LASCO) instrument on the Solar and Heliospheric Observatory (SOHO; Brueckner et al. 1995) white-light images (Figure 8) and in eclipse white-light images near the solar minimum of activity. An extended analysis of the activity in the polar regions was made by Wang et al. (1998) using the Extreme-ultraviolet Imaging Telescope (EIT) EUV filtergrams and the LASCO C2 images during the SOHO mission with a more limited spatio-temporal resolution compared to the present study. Note that these authors called the EUV eruptive phenomenon event producing a polar W-L dynamical structure a dynamical jet.

In Figure 10 we show more details and improve the visibility of the dynamical parts; the original intensities of plumes in each image were subjected to a running subtraction using a background image obtained after summing 16 minutes of consecutive images with a cadence of 12 s that run over the whole time sequence, pixel by pixel. In order to reproduce physically meaningful intensities we added a threshold to the result of the subtraction in Figure 5.

In the temporal evolution from the 304 Å images of the tornado the main components (or kernels) of the event are launched from the base with a constant proper velocity that has an average value of 140 ± 40 km s$^{-1}$ (from the analysis of Figure 7), and a rotational velocity with a similar value of 145 km s$^{-1}$ in this cool line. This filtering process allows us to separate short-lived dynamic phenomena from rather longer life-time background plume intensity variations.

The time–distance diagram along the axis of the tornado (Figure 7) in 304 Å line suggests that later the ejected plasma flows back to the Sun. This type of suggested complete parabola-motion path (e.g., Figure 7) is not seen in the 193 Å line. The longitudinal motion observed in Figure 3 is confirmed by the enhancement appearing later (see Figure 8) above the same polar region and the same radial position, over the occulting disk of the C2 coronagraph of LASCO. Wang et al. (1998) already reported a large correlation between the EIT jets and the long narrow white-light structures in the outer corona recorded using the LASCO observations. A large maximum value of velocity, of the order of 1100 km s$^{-1}$ for the leading edge of the white-light jets (the outermost part of the jet that can be visually seen and distinguished), was found.

The two-threaded 171 Å and 193 Å jets traveled at an apparent velocity of 140 km s$^{-1}$ in Fe IX (171 Å) and up to 600–1000 km s$^{-1}$ in Fe XII (193 Å) images, with a median value of 720 km s$^{-1}$ (Figure 10). 304 Å shows a speed of 140 km s$^{-1}$, similar to what is observed for 171 Å (Figures 3–5). Such values in He II line are also reported from EUV imaging spectrometer (EIS) observations by Kamio et al. (2010) for macrospicules seen that are associated with X-ray jets.

4. Conclusion

In this study we present detailed observations of a coronal hole jet, with a cool helical tornado-like structure at the feet and an extended hotter component in the radial direction. Our detailed analysis (Figures 9–11) shows that the propagation velocities are different for different line emissions and, accordingly, for different temperatures. In Figure 11 we show that at the highest level of the event the hot emissions occur first (also see Figure 10). This could suggest that the coronal heating is occurring first at higher levels where the densities are smaller.

The foot region is presumably above a well-developed 10$^{5}$ size network element (rosette) of the chromosphere. Recently Wedemeyer-Bohm et al. (2012) and Kitiashvili et al. (2013) considered an atmospheric tornado-like phenomenon as the result of a vortex magnetic structure driven by turbulence motions. It was also called a swirl with helical motion. Only a small-scale (1 Mm) region was analyzed (Wedemeyer-Bohm et al. 2012; Kitiashvili et al. 2013), while here we deal with a region one order of magnitude larger. A simple model which permits a twisted magnetic field could imply a self-sustained ring current dynamo occurring in the high photosphere (Lorrain & Koutchmy 1996; Veselovsky et al. 1999) to enhance the magnetic field, as a result of converging horizontal motion. We propose that the main steps of tornado evolution consist of three phases (see Figures 3, 9 and 10): (1) a precursor heating phase where new magnetic flux emerges to the reconnection site with heating by current sheet at the X-null point made by interacting loops, (2) the impulsive phase that begins when the cool chromospheric loops start to rotate, and (3) the main

![Figure 9. Average FWHM of the untwisting jet in 304 Å (see Figure 4), averaged over 5 pixels (3 arcsec) spatially and 5 steps (1 minutes) in time.](image-url)

![Cut images of the untwisting jet in 304 Å showing the propagation and rotation along the jet.](image-url)
Figure 10. Simultaneous fast successive snapshots during the initial phase of the ejection in different filtergrams. The white arrows point to the thin linear precursor jet of the tornado; it is seen in the hotter frames at 193 Å and is weaker in 171 Å. These frames are taken several minutes before the start of the tornado 304 Å event listed; see Table 1 and the future analysis in Figure 11.
The observation of a time difference between the hot linear jet-like feature and the ensuing tornado-like cool event suggests that the tornado helical formation is closely related to the precursor hot component that occurs when a release of energy occurs with the acceleration inside the tornado plasma vortex near the reconnection site. The SDO/AIA temporal and spatial resolution allows us to resolve some uncertainty concerning the relationship of hot line ejections and the cold tornado events at their footpoints. The detailed analysis of the behavior of different components of our event strongly supports the rather new suggestion that polar plumes (e.g., see Figure 1) are made of simple cylindrical structures of a $10^\circ$–$25^\circ$ diameter with an expansion in time, height, and width. A more detailed comparison with the substructure and the behavior of eclipse white-light polar plumes is needed (work in progress) to understand these structures. The forthcoming launch by European Space Agency of a novel coronagraph system (PROBA3 mission) permitting a total solar eclipse in space for several hours (Lamy et al. 2008) is another opportunity for making progress on this very old and classical question of explaining magnetic solar coronal polar plumes.

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**Figure 11.** Normalized intensity evolution for the three cuts along the jet, which are indicated in Figure 4. The red dots are for 193 Å, the green triangles are for 171 Å, and the blue squares are for 304 Å. The lines show the best Fourier-fitted data. The short black arrows show the beginning phase of the sharp ascent of averaged intensities for different lines. The heights of the cuts are shown in Figure 4. The thick black horizontal lines show the time difference of the ejection recorded in the cool TR (304 Å) line compared to the hot coronal line (193 Å).

phase, when the stored magnetic energy is released by ejection and untwisting.
