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Study of Coronal Jets During Solar Minimum Based on STEREO/SECCHI Observations

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Abstract During the 2007 – 2008 minimum of solar activity, the internally occulted coronagraphs SECCHI-COR1 onboard the STEREO space mission recorded numerous jet-like ejections over a great range of latitudes. We have found more than 10000 white-light jets in the above-mentioned period. Sometimes they can be identified on the disk with bright points observed in ultraviolet images by EUVI. In this study we present a catalog consisting of jets observed by the SECCHI-COR1 instrument and their association with lower coronal activity (bright points, UV jets). Furthermore, their association with bright points in the context of previously proposed models is discussed. From the complete catalog we have selected 106 jets observed in both STEREO-A and STEREO-B images for which it is possible to derive their kinematics and point of origin.

Keywords Jets · Corona, structures · Coronal holes · Solar wind

1. Introduction

Coronal white-light jets are narrow collimated ejections of plasma observed in coronagraphs field of view (FOV) (St. Cyr *et al.*, 1997; Wang *et al.*, 1998). They are mostly seen in active

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regions, quiet Sun, and coronal holes (Shimojo *et al.*, 1996). These events have been observed in soft X-rays by *Yohkoh* (Shimojo *et al.*, 1996; Shimojo and Shibata, 2000) and more recently by the *Hinode* (Kosugi *et al.*, 2007) X-Ray Telescope (XRT; Golub *et al.*, 2007), see Savcheva *et al.* (2007), Moreno-Insertis, Galsgaard, and Ugarte-Urra (2008), Raouafi *et al.* (2008), and Filippov, Golub, and Koutchmy (2009).

Shimojo *et al.* (1996) have analyzed jets originating in active regions, quiet Sun, and coronal holes using data from the Soft X-Ray Telescope (SXT) onboard *Yohkoh* (Ogawara *et al.*, 1991). They have found that 68% of the jets appear in or near active regions. They are also observed in ultraviolet (Alexander and Fletcher, 1999) and they are often associated with bright points (BPs) on the solar disk. These coronal jets are best observed inside polar coronal holes when the plasma beams are seen in emission against the dark background and are not obscured by bright ambient coronal structures (Nistico *et al.*, 2009).

Extensive work has been done on jets associated with polar coronal holes (St. Cyr *et al.*, 1997; Wang *et al.*, 1998; Wood *et al.*, 1999; Alexander and Fletcher, 1999; Kamio *et al.*, 2007; Savcheva *et al.*, 2007; Culhane *et al.*, 2007; Chifor *et al.*, 2008; Moreno-Insertis, Galsgaard, and Ugarte-Urra, 2008; Nistico *et al.*, 2009). Polar jets were studied during solar minimum activity (Wang *et al.*, 1998) using images from the Large Angle Spectrometric Coronagraph (LASCO; Brueckner *et al.*, 1995) and Extreme Ultraviolet Imaging Telescope (EIT; Delaboudinière *et al.*, 1995) onboard the *Solar and Heliospheric Observatory* (SOHO; Domingo, Fleck, and Poland, 1995). Wang and Sheeley (2002) later extended the study to include jets occurring inside or near the boundaries of nonpolar coronal holes near the maximum activity period. Wang and Sheeley (2002) found that these jets have angular widths of around $3^\circ - 7^\circ$, as measured from the Sun's center. These events have typical velocities of about 600 $\mathrm{km\,s^{-1}}$ and the tendency to be brighter and wider than the polar jets observed near sunspot minimum.

It is widely believed that coronal jets are the result of magnetic reconnection phenomena occurring in the solar corona (Shibata *et al.*, 1992; Yokoyama and Shibata, 1995, 1996; Pariat, Antiochos, and DeVore, 2009).

Since the launch of the *Solar TErrestrial RElations Observatory* (STEREO; Kaiser *et al.*, 2008) twin spacecraft in October 2006, more than 10000 white-light jets have been observed by the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard *et al.*, 2008) – COR1 coronagraphs. The latter are the primary data sources for the present study. We present a comprehensive catalog of the observed SECCHI-COR1 jets, with about 11 000 events in a two-year time frame starting from January 2007 and ending in December 2008. During this time the separation angle between the two spacecraft increased from 2° to 88°.

The coronal jets were identified and selected based on criteria that are explained in Section 2. A statistical study, including the velocity of 106 selected jets, their 3D coordinates, the correlation with UV jets and bright points observed by SECCHI-EUVI (Wuelser *et al.*, 2004) is analyzed in Section 3. The discussions and conclusions are given in Section 4. The complete catalog consisting of 10 912 jets, and the velocity catalog of 106 jets are annexed as electronic supplementary material.

2. Data Description

2.1. Instrument Description

The SECCHI experiment on the STEREO mission is a suite of remote-sensing instruments consisting of an Extreme Ultraviolet Imager (EUVI), two white-light coronagraphs (COR1 and COR2) and two heliospheric imagers (HI1 and HI2). COR1 coronagraph is a classic Lyot internally-occulted coronagraph, which observes the white-light corona from 1.4 $R_\odot$ to 4 $R_\odot$ (Thompson *et al.*, 2003). The coronagraph includes a linear polarizer, which is used to suppress scattered light and to extract the polarized brightness signal from the solar corona. The polarized brightness is obtained from three sequential images taken with polarization angles of 0°, 120°, 240°. The EUVI observes the chromosphere and low corona in four narrow filter bands around spectral lines Fe X/Fe XI 17.1 nm, Fe XII 19.5 nm, Fe XV 28.4 nm, and He II 30.4 nm.

2.2. Identification Criteria

To identify the white-light jets we used running-difference COR1 daily movies (Figure 1, top panel), available at http://cor1.gsfc.nasa.gov/dailymov/. The imaging cadence for the above-mentioned movies is 20 minutes, though there are exceptions. Jets appearing in only one frame were considered to have a life time smaller than 20 minutes. Only intense jets with a life time greater than 20 minutes (meaning that they are visible in at least two frames) were considered for correlations with their EUVI corespondents and BPs. Note that in this way short-living and faint jets were not considered for correlation. From the total number of events we have also ignored any "jet-like" features with the angular width larger than 8° relative to the Sun center.

In order to correlate white-light jets with on-disk and lower-coronal features (Figure 1, bottom panels) we have used the STEREO-EUVI 19.5-nm images (coronal temperatures of 1.6×10^6 K) provided by the Solar Weather Browser (SWB) software available at http://sidc.oma.be/SWB/ (Nicula, Marqué, and Berghmans, 2008). Certain periods were not available in SWB, therefore images from the STEREO Science Center website were used instead: (http://stereo-ssc.nascom.nasa.gov/cgi-bin/images). EUV images were recorded with a 10 minutes rate. Due to the presence of large-scale coronal bright structures, sometimes faint jet-like structures could not be identified in EUVI data.

The resulting catalog consisting of 10 912 events can be found as attached supplementary material and provides information on each column as follows: the date in the format mm/dd/yy when the jet was observed, the time when the jet was first seen in COR1 FOV, the time of the last frame where the jet was still visible in COR1 FOV, the position angle (PA; measured counterclockwise from the projected solar North pole). This information is present for events observed in COR1-A and/or COR1-B. The last two columns are reserved for the correlations with BP (first column) and with EUV jets (second column). The inspection of COR1 running-difference frames was done visually, using a (r, θ) grid similar to that from the SWB, but with a theta of 10°, and as a consequence the PA was measured with an estimated precision within ≈10°.

From the above 10 912 events, 1732 have a life time longer than 20 minutes. These events were used for correlation with BPs and EUVI jets. From the correlated events, a subset of 106 events that were observed simultaneously by both SECCHI-A and -B is used to determine the velocity and 3D coordinates of the corresponding jets. In order to achieve this goal, COR1 images recorded at different polarization states are utilized. As the white light in the solar corona is polarized tangent to the solar limb (Billings, 1966), certain polarizations are suitable for certain position angles. For instance, the 0° polarization is best for jets originating near the equator, the 120° and the 240° can be used for events occurring near the poles.

To assess jet velocities and their 3D coordinates we have used the programs available in the SolarSoft package: `scc_wrunmoviem` and `scc_measure`, respectively. The results

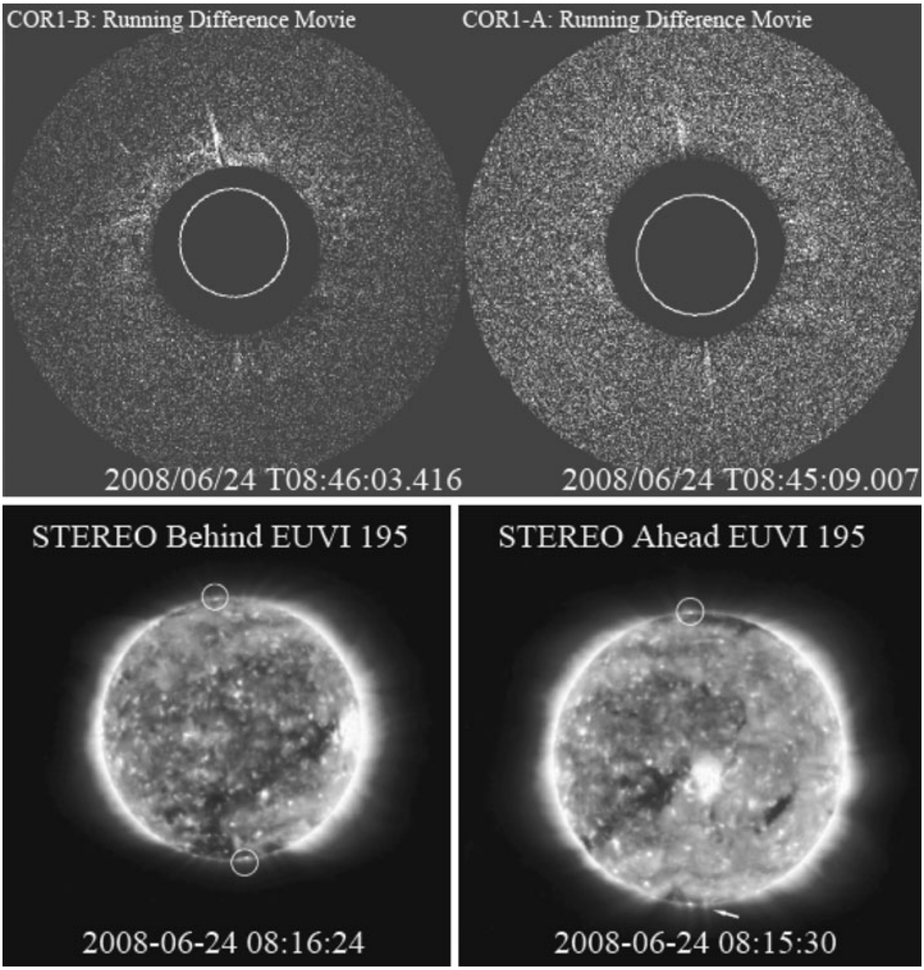

Figure 1 Solar jets seen in both SECCHI-COR1 (top panels) and SECCHI-EUVI (bottom panels) images. In the bottom panels the encircled areas contain bright points that are associated with the jets. The arrow points to a jet, which in the image cannot be correlated with a visible bright point. (Images courtesy of the STEREO-SECCHI consortium.)

are provided in the velocity table (as electronic supplementary material). The structure is similar to that of the general catalog, with additional columns for velocity, three dimensional coordinates (longitude and latitude) and the polarized angle where the jet was best observed. Comparing these results with the correlation phase we can truly assess the accuracy of the data.

3. Statistical Study

Among the 10 912 events, 1874 jets are seen in both COR1-A and COR1-B as corresponding to the same events in 3D. 4909 jets can only be observed in COR1-A, while 4129 can be observed only in COR1-B. The largest number of jets was observed in July 2008 (539 jets)

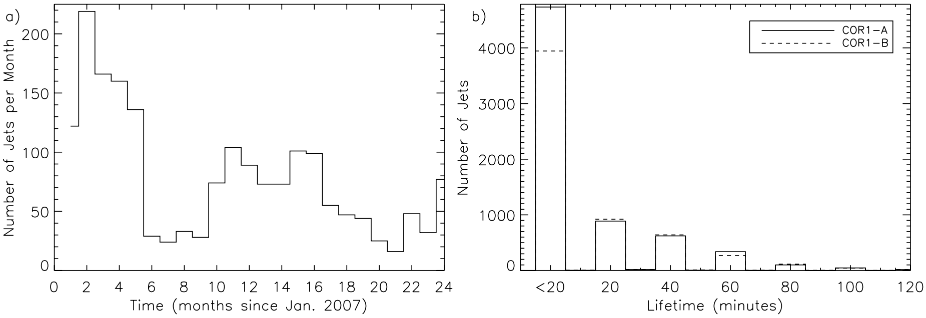

Figure 2 (a) Histogram of events observed simultaneously by COR1-A and COR1-B per month. (b) Life time histogram of all observed jets (bin size/time precision is 20 minutes).

Table 1 Jets' life time (in minutes).

	COR1-A	COR1-B	COR1-A + COR1-B
Number of events	6783	6003	1874
Average life time	12	13	24
Dominant life time	≤20	≤20	20

in COR1-A, and in January 2008 (510 jets) in COR1-B. Because the distance between the two satellites is steadily increasing, most of the jets observed from both perspectives are recorded in the first half of 2007. (See Figure 2(a).)

3.1. Coronal Jet Life Times

Figure 2(b) displays the jets' life time histogram. We defined the beginning of the jet to be the moment when a little spike of brightness starts to appear from behind the occulter and becomes visible in running-difference images. Similarly, the end of the jet was set to the moment when the jet was last observed (as a bright feature) in running-difference images. Due to the temporal resolution of 20 minutes between the frames, the life times are multiples of 20 with the exception of a few cases when the temporal resolution was different. As a consequence, the errors in estimating the life time may go up to 20 minutes. The average and dominant life times are presented in Table 1. To get the mean value, we set the life time of small jets (observed in only one frame) at 0 minutes.

3.2. Distribution of Jets *versus* Position Angle (PA)

The majority of the observed jets peak at around 0° (COR1-B) and 180° (COR1-A) (see Figure 3). Some minor peaks can be observed at 0°, 220° and 240° for COR1-A events, and 120°, 180° and 240° for COR1-B events. Table 2 summarizes the number of jets at various position angles. It can be seen that most jets originate in polar coronal holes.

3.3. Correlation with EUVI Features

The correlation of jets having a life time larger than 20 minutes with BP and EUV jets was done by visual inspection using SWB. A movie of combined EUVI and COR1 images was created for each observed jet and any modification in EUVI images associated with the

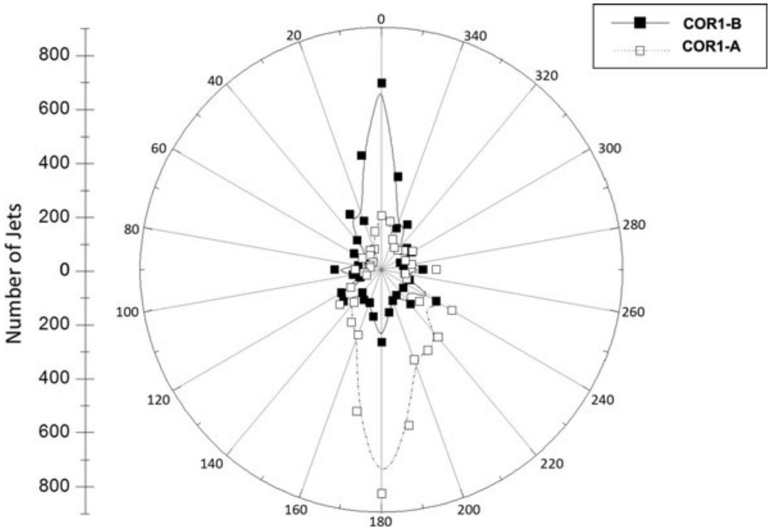

Figure 3 Polar distribution of events seen from COR1-A (empty squares fitted with the dotted line) and from COR1-B (filled squares fitted with the continuous line). The radius of each circular cut represents the number of jets. The position angle is measured from the top of the plot, counterclockwise. The data were fitted using a B-spline function.

Table 2 Jet distribution by position angle.

	COR1-A	COR1-B	COR1-A + COR1-B
Total number of jets	6783	6003	1874
North $330 \leq \mathrm{PA} \leq 30$	899	2237	541
South $150 \leq \mathrm{PA} \leq 210$	3129	1099	629
East $60 \leq \mathrm{PA} \leq 120$	525	786	159
West $240 \leq \mathrm{PA} \leq 300$	1032	872	271

moment when the jet was observed in COR1 was investigated for a possible correlation. To avoid confusion, we first correlate white-light and EUV jets. By EUV jets we mean jet-like structures observed in EUVI 19.5-nm images. The second step was to find the sources of EUV events that correspond to positive correlations (the events rooted at the far side were eliminated from the final count). In this way, the white-light jets could be associated with EUV jets and/or bright points. Note that for jets observed in both COR1-A and COR1-B we have applied a positive correlation at the moment we have seen that the jet was correlated either in A or B images. As we mentioned in Section 2, due to bright coronal structures it is possible to miss some of the EUV events associated with COR1 jets. Also, it may be that the BP was on the back side of the Sun. Some BP that were near the jet emission were not taken into consideration as a possible source region because no change in the morphology and brightness was observed, and because no jet was observed in EUV images. Note that some bright points have a transient behavior and are really short-lived. They do not show much of a change in the brightness or intensity output. Some others are very faint. This makes their identification tricky and this may explain the rather low correlation rate between white-light jets and BPs. There were cases of larger bright points (mini active regions) that did not change morphology but a EUV jet could clearly be associated. Table 3 presents

Table 3 Correlation of white-light jets with EUV jets and BPs.

	COR1-A	COR1-B	COR1-A + COR1-B
Number of events	1090	1143	501
BP Association	51%	51%	58%
EUV Jets Association	75%	73%	78%

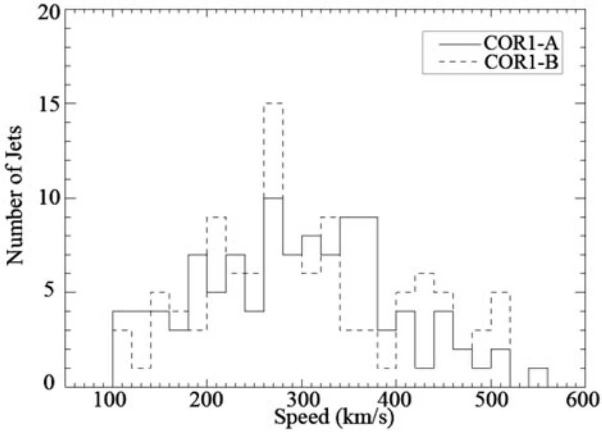

Figure 4 Histogram distribution of jets projected velocities. The overall distribution is similar to Figure 4 from Savcheva *et al.* (2007), though a shift can be observed.

the percentage of jets having a life time longer than 20 minutes that we have found to be correlated with EUVI coronal features, namely EUVI jets and BPs.

3.4. Speeds and Position Analysis

With the STEREO data we can assess the jet's position in space and establish its true velocity. In this way we can understand projection effects that are present in single point observations (Inhester, 2006; Aschwanden *et al.*, 2009; Mierla *et al.*, 2009).

The estimation of the projected speeds of each jet was based on the following steps.

i) Identification in COR1 running-difference images of the leading edge (LE) of the jet at an instant of time.
ii) Tracking the LE in successive time-lapse images in the COR1 field of view.

Once the height-time (HT) diagram was built, a linear fit or a second-order polynomial fit was applied to obtain the outflow speeds. In most cases a linear fit was sufficient, implying that the jets were moving at a constant speed in COR1 FOV. Recently, Mierla *et al.* (2008) used the 3D-HT technique on the images acquired by COR1 coronagraphs aboard SECCHI/STEREO spacecraft. This technique involves obtaining height–time plots for a well identified feature in the CME from its observation in two STEREO images. This yields two independent projected velocity vectors, from which a 3D velocity vector can be constructed. In this study we investigated only the behavior of the projected speeds of 106 events observed simultaneously in COR1-A and COR1-B images. The full velocity vectors will be included in a future work. The speeds that were obtained vary, with an average of $\approx$300 km s^{-1}. Figure 4 shows that the majority of jets have speeds ranging from 180 to 380 km s^{-1}.

To obtain the 3D coordinates we used a tie-pointing method in the stereoscopic images taken by COR1-A and -B coronagraphs which contain the jet. In order to identify the same

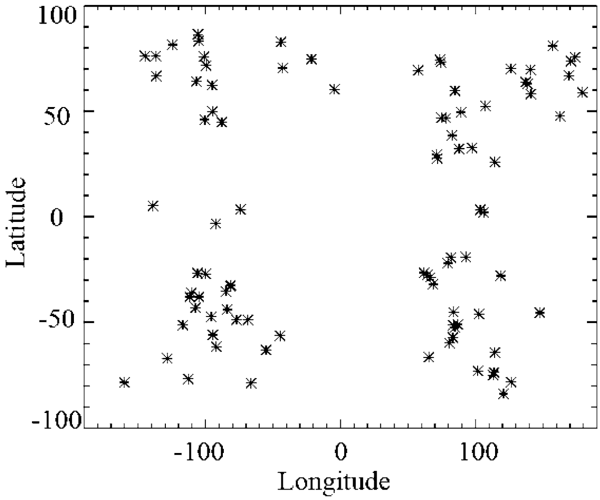

Figure 5 Position of jets on heliographic coordinates. It can be clearly seen that almost all jets have a longitude which places them near the limb.

structure in the two images we used running-difference images. Further, we used the routine called scc_measure.pro (available in the SolarSoft package) to reconstruct the 3D coordinates of the selected point along the jet at an instant. This procedure gives the reconstructed coordinates in terms of heliographic latitude, longitude and distance from the Sun's center. The 3D positioning (see Figure 5) shows that almost every jet analyzed was located near the limb. This behavior is due to Thomson scattering properties, which maximize the jet intensities at the plane of the sky, as at normal angles from the Sun the scattered light is maximized. Some polar jets appear to originate beyond the visible range, though they are correlated with observable EUV bright points. This can be explained by the high latitude at which these jets originate.

4. Discussions and Conclusions

The main purpose of this work was to identify and study white-light jets observed by SECCHI-COR1. All of the past studies focused on jets coming from coronal holes.

All jets observed at minimum of solar activity between 2007 and 2008 by SECCHI-COR1 are included. We have identified more than 10 000 white-light jets all over the solar disk. The identified jets originate from regions inside coronal holes, but also from regions of the quiet Sun. From these jets, 1732 have a life time longer than 20 minutes and they were considered for correlation with bright points on the solar disk. The association was established based on the observed changes (morphological, brightening, disappearing *etc.*) of the BP as observed in EUVI 19.5-nm images at the time when the jet was observed in COR1. All these BPs were located in regions close to the solar limb. When the BPs are observed on the solar disk, closer to the center of the Sun, it is difficult to associate any EUV jet-like structure because of the bright background on which the jets project. This implies that the number of jets is much larger than the number of those studied here.

Given the large number of such observed events and the amount of energy each jet may release, their study is a valuable input for coronal heating models.

There are different possible mechanisms responsible for the jets production. Polar jets are believed to occur when reconnection between small-scale, pre-existing or emerging, closed magnetic fields and open, large-scale magnetic field lines of coronal holes take place (Shibata *et al.*, 1992; Yokoyama and Shibata, 1996; Moreno-Insertis, Galsgaard, and Ugarte-Urra, 2008; Pariat, Antiochos, and DeVore, 2009). The energy released via magnetic reconnection increases the gas pressure in the reconnected closed loop, producing a small flaring loop and a jet. An alternative version of the above-mentioned scenario is discussed by Filippov, Golub, and Koutchmy (2009) and the references therein. They proposed a qualitative model of jet formation within the dome-like magnetic configuration in which the energy source of the process is not energy released in a reconnection site but free magnetic energy of a small twisted flux tube. Evidence of the helical twist in a EUV polar jet was found by Dere *et al.* (1999), and Neupert *et al.* (1998) using SOHO data and by Patsourakos *et al.* (2008) using STEREO data. They found that the jet's body appeared to untwist while rising and proposed the magnetic untwisting as a driving mechanism for the initiation of polar jets.

The number of jets with high outflow speeds is reasonably large, enough to contribute significantly to the solar wind (see also Filippov, Golub, and Koutchmy, 2009).

Solar jets may have various morphologies and kinematic properties. Nistico *et al.* (2009) analyzed the morphology of 79 polar jets observed with SECCHI-EUVI and SECCHI-COR1 instruments in the period March 2007 – April 2008. They have found 37 Eiffel tower-type jet events commonly interpreted as a small-scale magnetic bipole reconnecting with the ambient unipolar open coronal magnetic fields at its looptops, and 12 lambda-type jet events commonly interpreted as reconnection with the ambient field happening at the bipoles footpoints. They have estimated an outward propagation speed of 400 $\mathrm{km\,s^{-1}}$ in EUVI 17.1-nm images and 270 $\mathrm{km\,s^{-1}}$ in EUVI 30.4-nm images. The speed we have estimated for 106 jets in COR1 FOV over a period of two years were between 100 and 560 $\mathrm{km\,s^{-1}}$. The overall distribution is similar to that of Savcheva *et al.* (2007), the only difference being the peak distribution: 160 $\mathrm{km\,s^{-1}}$ for the jets analyzed by Savcheva *et al.* (2007), and 270 $\mathrm{km\,s^{-1}}$ for the jets studied here. Their conclusion was that they could use these results to point to the mechanism for expansion of the jet, namely a pressure-driven expansion of the plasma. Note that we have used white-light images from 1.4 $R_\odot$ to 4 $R_\odot$, while Savcheva *et al.* (2007) have used X-ray images up to 1.4 $R_\odot$. Wang *et al.* (1998) and Wang and Sheeley (2002) have analyzed the white-light jets observed by LASCO at minimum and maximum of activity, respectively. At minimum of activity they have found speeds in the range of 400 to 1100 $\mathrm{km\,s^{-1}}$ for the leading edge and 250 $\mathrm{km\,s^{-1}}$ for the bulk of their material. The typical velocities at maximum of activity were around 600 $\mathrm{km\,s^{-1}}$.

The solar jets also have a large range of life times. The majority of jets in our data set have a life time smaller than 20 minutes. Savcheva *et al.* (2007) have found a 10 minutes life time for the majority of jets observed by XRT on *Hinode*. Nistico *et al.* (2009) have found that the typical life times in the EUVI FOV are 20 min in 17.1 nm and 19.5 nm, 30 min at 30.4 nm, while in COR1 the life times are peaked at around 70 – 80 min. It may be that events seen in COR1 are only the most prominent ones, and thus only long-lived prominent jets can make it to the COR1 FOV. During this study some interesting jet events were selected. Those events along with a more thorough analysis of the parameters discussed above as well as other characteristics will be studied in future work to constrain the models for the reconnection occurring in the solar corona and their possible contribution to the heating of the solar corona.

To our knowledge this is the most extensive catalog of white-light jets to be published, and it could be a landmark of future research.

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