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The Analysis of Polar Jet Responses Using Images From the LASCO C2 and STEREO COR 2 Coronagraphs

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Abstract. High cadence images taken by the X-Ray Telescope (XRT) onboard *Hinode* and the Solar Dynamics Observatory Atmospheric Imaging Assembly (AIA) instrument provide an opportunity to observe solar jetting activity. The brightest several of these polar jets show a positive correlation with high-speed responses traced into the interplanetary medium, and have been reported in the full SMEI (Solar Mass Ejection Imager) data set images at large solar distances in the heliosphere where they retain a semblance of their original identity. LASCO C2 and STEREO COR 2 coronagraph images allow measurements of the coronal response to some of these jets, and the nearby background solar wind velocity, giving a determination of their speeds and energies that we can compare with *Hinode* and AIA observations. In this preliminary study we document two of these solar jet traversals into the inner heliosphere in the region intermediate to this region and the XRT and AIA observations.

Keywords: Solar Corona, Coronal holes, Solar Wind, Coronal Mass Ejection, and Solar Wind Plasma
PACS: 96.60.P-, 96.60.pc, 96.60.Vg, 96.60.ph, and 96.50.Ci

INTRODUCTION

Results from the *Hinode* spacecraft X-Ray Telescope (XRT) [1] and the NASA Solar Dynamics Observatory (SDO) Atmospheric Imaging Assembly (AIA) instrumentation [2], reveal that X-ray bright points and the corresponding jetting activity are more numerous, than originally thought [3]. Only the brightest of these explosive events had been previously observed and well-studied; much detailed work has gone into the analysis of these individual events, their manifestations, and the mechanism of plasma acceleration near the solar surface [e.g. 4, 5]. However, their character was always somewhat in doubt. Images from the SOlar and Heliospheric Observatory (SOHO) and the Solar TErrestrial RElations Observatory (STEREO) [6] have revealed that polar jets can extend out beyond a solar radius and are related to plumes, which are ubiquitous in coronal holes. Although previous studies have also shown that jetting activity either initiates or enhances the outward flow (assumed to be of the solar wind) in polar plumes observed in coronagraph data [7, or see review, 8], seldom have jet manifestations been followed through coronal regions and into the heliosphere in order to map their contribution to the solar wind and characterize their energy budget in relation to the solar wind background. Recent evidence of enhanced densities associated with jet responses are reported in the full sky map data sets from the Solar Mass Ejection Imager (SMEI) and in IPS observations [9]. In order to accurately trace these same jet manifestations seen from the solar surface into the heliosphere they must also be seen in observations intermediate to the two extremes (XRT/AIA and SMEI/IPS observations). In this article, we document two polar jet responses and the techniques we use to trace the trajectories of these outward from the solar surface in coronagraph data sets.

DATA SETS AND 2D CROSS-CORRELATION TECHNIQUE

During the campaign mode survey period from 5 to 22 September 2007, *Hinode* Observing Proposal (HOP-40), XRT images restricted to cover less than the full solar disk, can then be obtained continuously at a high temporal cadence. Sako et al. [9] found nearly 850 jets inside and around the northern coronal hole region over the three-week HOP-40 survey interval. Figure 1 shows one full image and two enlarged frames in the high-cadence (~1 min per image) sequence of one of the brightest X-ray jets near the northern polar coronal hole boundary measured on 14 September 2007. These images that provide measurements in solar polar regions show solar jets and the location of the vertically-oriented nearby flux tube structures [10]. The jet response moves away from the Sun non-radially and eastward relative to its solar surface location.

Jackson *et al.* [11, 12] have developed a 2D IDL cross-correlation technique to measure coronagraph optical flow ([13], and references therein) and have used this technique on the Large Angle Spectrometric

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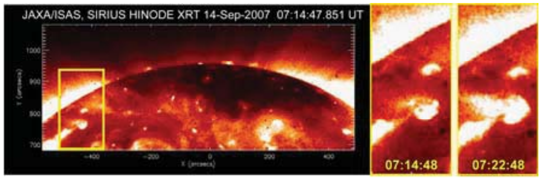

FIGURE 1. *Hinode* XRT data showing the north solar pole region, imaged in campaign mode in September 2007. The two right panels show an enlarged region of the jet response on 14 September 2007 at the time indicated (at 56ºE, 57ºN in ecliptic coordinates relative to the Sun center observed from Earth). The jet ejecta response moves away from the Sun non-radially and eastward relative to its solar surface location.

COronagraph (LASCO) C2 coronagraphs on SOHO [14]. Figure 2 shows a LASCO C2 background subtracted image overplotted with the blue-colored speed results at 2.8Rs obtained from 2D cross-correlation (left-panel). Direct coronagraph images show this small brightness enhancement moving outward with a constant plane-of-the-sky speed of 420km/s and an onset within minutes of the bright flare. By correlating an image patch located at 2.8 Rs with small patches taken within the yellow sector in the next image, we obtain the location of correlated features within the image to determine the optical or pattern flow of the outward-moving structures. The right panel of Figure 2 shows the summary plot of the speed distribution of these features over different heights and azimuth angles. The coronal disturbance associated with the *Hinode* jet on 14 September 2007 is shown to move outward from the Sun at a speed higher than 400km/s in these correlation plots.

These, and similar observations of possible jetting activity viewed in the inner heliosphere [15] provided a background for *Hinode* Observing Proposal (HOP-187) "Tracking X-ray Jets from the Solar Surface to Interplanetary Space"[16]. This exercise was a

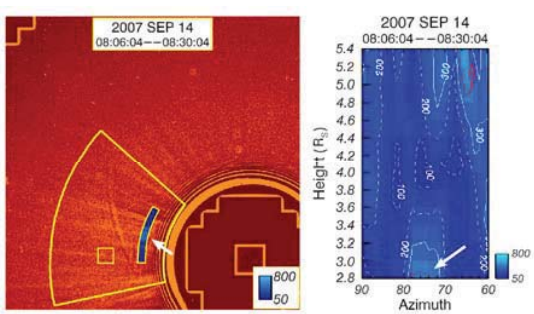

FIGURE 2. LASCO C2 background subtracted image overplotted with the blue-colored speed results at 2.8Rs obtained from the 2D cross-correlation (left-panel). The speed summary plot at different heights and azimuth angles is presented in the right panel. The jet response is marked by the white arrow.

coordinated effort to gather data from a large number of spacecraft and ground-based instruments, both to study the polar jetting process and to allow tracing the jet response into the heliosphere in a statistical manner. These observations can utilize all of the spacecraft and ground-based information available during the HOP-187 periods on 17 June and 22 August 2011, including those from the LASCO C2 coronagraph operated at high cadence specifically for the purpose of this HOP. The LASCO coronagraphs [17], when run in high cadence, have observed polar plumes, often with rapidly moving onsets and continuous outflow, with velocities of hundreds up to a thousand kms^{-1} [7, 18]. These observational results show that polar plumes are often associated with jetting activity and that they originate near extreme ultraviolet (EUV) bright points. Unlike LASCO, the STEREO COR observes polar plumes from a non-Earth perspective many degrees away from Earth along the ecliptic. The coronagraph views obtained from LASCO and STEREO located distant from each other can be used to build a 3D perspective view of solar plumes and jetting activity.

SDO AIA data sets provide a wealth of information about the associated solar surface changes pertinent the jetting phenomena from this instrument on a day-to-day basis. During HOP-187 we were able to view jetting activity from the southern polar coronal region in both AIA and XRT high-cadence observations.

In this analysis (and as also shown in Figure 2) the XRT [19] run in "campaign mode" onboard the *Hinode* spacecraft, and finely-resolved spectral images from SDO AIA instrumentation define the location and timing of the jetting observed near the solar surface. Images from the LASCO C2 coronagraphs on SOHO and from STEREO COR 2 (CORonagraph) [6] confirm their coronal response. We apply direct measurements and a 2D cross-correlation technique on both the C2 and COR 2 successive coronagraph images to determine the high speed jet response associated with XRT or AIA.

LASCO C2 AND STEREO COR 2 CORONAL FLOW

Using data from the HOP-187 period, we have tracked one large jetting response from the solar surface into both the LASCO C2 and COR 2 fields of view. The large jet was observed at ~02:50 UT 17 June 2011 by the SDO AIA instrument. As shown in Figure 3a, this jet-like feature was located in the southern coronal hole region. Identified by onset or enhancement timing of the outward motion observed in both the LASCO C2 and STEREO COR 2, we were able to follow this jet response in both instruments. During HOP-187 the LASCO C2 coronagraph was

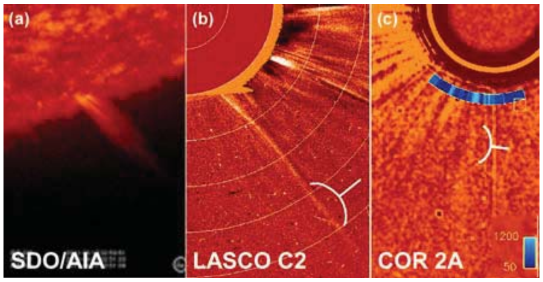

FIGURE 3. (a) SDO AIA jet observed during the HOP-187 period at ~02:50 UT on 17 June 2011. (b) LASCO C2 coronagraph enhanced image of the jet response. The bracket shows the location of the jet feature that is associated with the most intense portion of the jet response in SDO AIA images. (c) COR 2A (STEREO ahead spacecraft) coronagraph image of the jet response. The bracket shows the structure that is associated with the same feature observed in the AIA images. Superimposed on this image is the 2D cross correlation velocity determination provided at 3.6 Rs from this and the following coronagraph image. A high velocity region (see light blue band) is observed associated with the highlighted structure.

operated to view the south polar coronal region at an enhanced cadence of 5 minutes and with a 100-second exposure time that was 4 times longer than the nominal value. The enhanced C2 image (Figure 3b) shows a pre-existing plume structure in the southern coronal hole region. This jet manifestation is observed as a bright enhancement of a propagating "kink" that moves along the plume structure at a speed of about 1300 kms^{-1} on the sky plane and again, as in the response observed for the 2007 jet response, with an onset nearly identical in time to the AIA jet. Figure 3c shows the image of a bright feature that propagates outward at approximately the same speed in the COR 2 coronagraph data. Two sets of height-time plots shown in Figure 4 indicate motion at the centroid of this outward propagating coronal structure. Figure 4a shows the location of the structure in the plane of the sky (elongation versus time) and 4b shows the corrected location for its out-of-the-sky-plane motion assuming this is a view of the same feature that is progressing outward from the Sun. The speed of the jetting activity shown in Figure 4b is calculated to be ~1330 kms^{-1}, and shows a feature with no apparent deceleration to a height of about 14 Rs. The structure viewed in each coronagraph direct image appears to be outward-moving bright material and an enhancement over the existing structure with the same high speed response in both LASCO C2 and COR 2 instruments that are about 90° in longitude from each other. Figure 5 shows a synopsis of correlation results from LASCO C2 (left) and COR 2 (right) similar to those shown in Figure 2 (right). The arrows locate the jet responses in the two measurement sets which are 90° apart. The high speed jet regions are clearly observed as short-lived patches of high speed wind in these correlation measurements. This jet region in the Figure 5 plots moves outward at speeds of over 1200 kms^{-1}, and thus confirms that the optical flow correlations measure nearly the same speed as those determined directly from the coronagraph images. The characteristic size of these regions is ~1.5 Rs long and 3° wide, about the

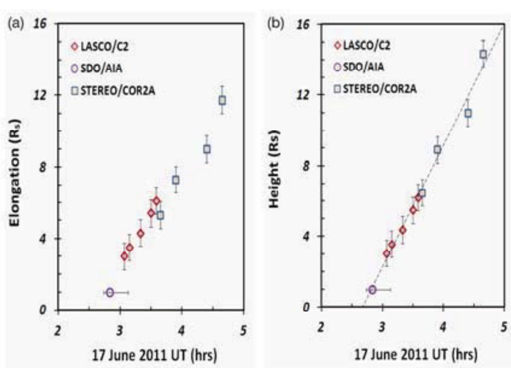

FIGURE 4. The height-time plots of the outward motion of the jet shown in Figure 3a. The structure's centroid is measured; the vertical bars indicate the radial extent of the outward moving structure, and the horizontal bar on the jet response at 1 Rs indicates the duration of the brightest portion of the jet ejecta observed in AIA images. (a) outward progression of the jet response on the sky plane. (b) outward progression in height (the distance from the center of the Sun).

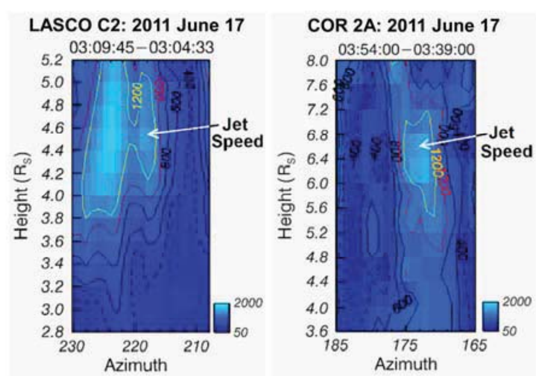

FIGURE 5. Synopsis of the speed measured with height in the regions surrounding the locations of the jet responses observed in two successive coronagraph images. The arrow locates the jet response in the two measurement sets. The analysis program shows that the jet response moves outward at speeds of >1200 kms^{-1}. (left) LASCO C2 synopsis. Other fast outward motions are recorded near the jet response. (right) COR 2A synopsis. The fast region extent is ~1.5 Rs.

same size as the structures observed in the direct coronagraph images. These analyses thus confirm the extremely high flow speeds associated with the jetting activity from a specific location within the southern polar coronal hole.

SUMMARY AND DISCUSSION

We show several bright jets appearing within the polar region during the HOP intervals in XRT and AIA observations that have discernible associated high-speed coronal enhancements in LASCO coronagraph images. We have developed a systematic method to provide a measurement for these jetting responses in coronagraph observations. The high-speed response measurement observed during the HOP-187 period in LASCO C2 and STEREO COR 2 coronagraph images show a structure moving outward at a speed of over 1200 kms^{-1} in association with the AIA jet, and, as in the measurements shown during the HOP-40 period in 2007, have a characteristic size of a few Rs long and several degrees wide. These are high-speed slightly-enhanced density regions intermediate to the observations of them in both XRT/AIA and inner heliosphere IPS/SMEI observations. We thus feel these results that show small bright structure enhancements in both the direct and correlation analyses of the same jet response and for the one example in both C2 and COR 2 observations 90° in longitude apart have the most likely explanation as measurements that are not of a wave phenomena but actually of material flow. Wang *et al.* [7] measure jet-associated flow speed in enhanced LASCO C2 images, and their analysis indicates that there is a decrease in the outward speed following the jet response onset. From the synopsis of the speed measured with height in the regions surrounding the jet responses in Figure 5, we also determine that slow flow follows the short-lived high-speed jet patches, and so we also show that outward flow near plumes does not remain constant. Moreover, with such high speeds observed in the lower corona surrounding jetting regions, there should be some manifestation of these regions present in the lower heliosphere that can be measured by the SMEI analysis and by IPS (interplanetary scintillation) velocities as noted in [15] and shown for the jet response of June 17 in recent reports [20].

We note in the correlation plots of coronagraph images (such as Figure 5 - left) that there are other coronal regions that appear to show similar high speeds that are not necessarily associated with jetting activity. We leave as future exercises a study of the jet response speed relationship relative to the background solar wind flow measured by other techniques in the same coronal regions in order to better certify their coronal identity and reality as material flow.

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