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EVIDENCE FOR POLAR JETS AS PRECURSORS OF POLAR PLUME FORMATION

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ABSTRACT

Observations from the *Hinode*/XRT telescope and *STEREO*/SECCHI/EUVI are utilized to study polar coronal jets and plumes. The study focuses on the temporal evolution of both structures and their relationship. The data sample, spanning 2007 April 7–8, shows that over 90% of the 28 observed jet events are associated with polar plumes. EUV images (*STEREO*/SECCHI) show plume haze rising from the location of approximately 70% of the polar X-ray (*Hinode*/XRT) and EUV jets, with the plume haze appearing minutes to hours after the jet was observed. The remaining jets occurred in areas where plume material previously existed, causing a brightness enhancement of the latter after the jet event. Short-lived, jetlike events and small transient bright points are seen (one at a time) at different locations within the base of preexisting long-lived plumes. X-ray images also show instances (at least two events) of collimated thin jets rapidly evolving into significantly wider plumelike structures that are followed by the delayed appearance of plume haze in the EUV. These observations provide evidence that X-ray jets are precursors of polar plumes and in some cases cause brightenings of plumes. Possible mechanisms to explain the observed jet and plume relationship are discussed.

Subject headings: Sun: corona — Sun: magnetic fields — Sun: UV radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

Recent space missions, such as *Hinode* (Kosugi et al. 2007) and *STEREO* (Kaiser et al. 2008), and ground-based facilities such as SOLIS (Keller et al. 2003), provide a set of data unprecedented in quality and cadence. The complementary observations from the different instruments provide the necessary spatial, temporal, and temperature coverage to observe the dynamics of jets and polar plumes, helping to form a more complete picture of these structures.

X-ray jets occur almost everywhere in the solar corona (see Shibata et al. 1992), in particular in the polar holes. They are characterized by their transient nature and often appear as a collimated high-temperature emissive beam guided by open magnetic flux (length of 10^5–10^6 km and collimated widths of ~10^4 km; see Cirtain et al. 2007). Cirtain et al. (2007) reported that the plasma outflow speeds within X-ray jets range from ~100 to ~1000 km s^{-1} and that Alfvén waves are responsible for the high outflow velocities.

In contrast, polar coronal plumes are observed to be hazy in nature without sharp edges, as seen in extreme-ultraviolet (EUV) images from *SOHO*/EIT (Delaboudinière et al. 1995) and *STEREO*/SECCHI/EUVI (Howard et al. 2008). Plumes are also observed to be significantly wider than X-ray jets (~20–40 Mm; see Wilhelm 2006) and reach several solar radii in height (see DeForest et al. 1997). Plumes are brighter and cooler and the plasma outflows are smaller than in interplumes (see DeForest et al. 1997; Wilhelm et al. 1998; Raouafi et al. 2007).

Recent studies of jets and polar plumes (X-ray and EUV; see Wang 1998; Moreno-Insertis et al. 2008) treat these coronal structures independently, and the relationship between them is not investigated. The present research is motivated by the fact that polar X-ray and EUV jets and plumes usually share common properties. Both are episodic in nature and occur at magnetic field concentrations that coincide with the chromospheric network where both structures form through flux emergence (see Canfield et al. 1996; Wang 1998). Studying the relationship between jets and plumes is important to understanding their formation processes and evolution and the eventual contributions to the solar wind and heating of the plasma in the polar coronal holes. The present work is motivated by the observations of polar jets evolving into plumes such as the one shown in Figure 1. The aim of the Letter is to investigate the relationship between these prominent coronal structures.

2. OBSERVATIONS AND DATA ANALYSIS

The XRT telescope (Golub et al. 2007) on *Hinode* provides high-resolution images (≈1″–2″ depending on the location within the field of view) of the solar corona at temperatures ranging from 1 to 20 MK. Observations of the southern coronal hole from XRT were utilized to study the evolution of polar X-ray jets and their relation with plumes. The data cover several time intervals on 2007 April 7–8 (April 7: 03:30–06:59 UT and 18:29–23:59 UT; April 8: 11:49–17:59 UT and 21:30–22:59 UT) with a cadence of less than a minute. The data were corrected for instrumental effects utilizing XRT calibration procedures.

A total of 28 X-ray jets were identified, with at least two recurring events within an hour. Most of the events are characterized by sharp collimated beams. The observed jets have different properties with regard to brightness, spatial extension, lifetime, and evolution. The bright point at the base of each jet is enhanced in brightness with every eruption and then fades after the jet is no longer observed.

In addition, 171 Å images from the *STEREO*/SECCHI satellite "A" were utilized to study EUV features in relation to the identified X-ray events. Particular attention was given to the presence of plume material during or after the eruption of jets. The choice of 171 Å was dictated by the adequate temperature corresponding to polar plume emissions.

3. RESULTS

Figure 2 displays the line-of-sight chromospheric magnetogram (Ca II 8542 Å) of the south pole on 2007 April 7 recorded by the SOLIS/VSM instrument (Henney et al. 2008).

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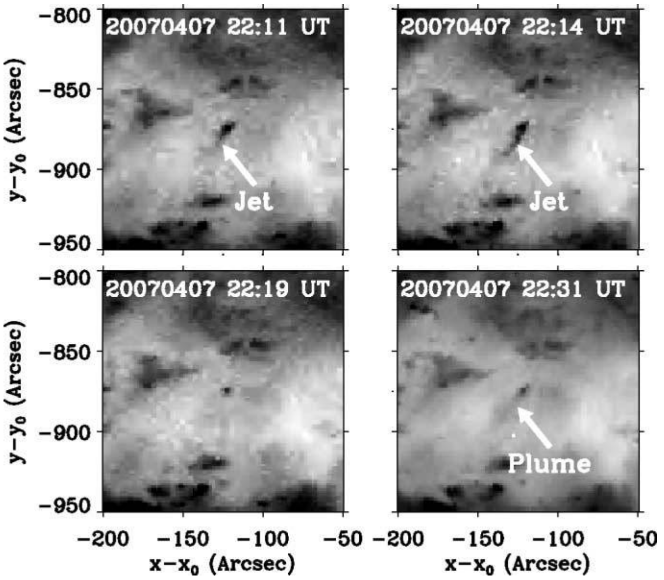

FIG. 1.—*STEREO*/SECCHI/EUVI "A" images illustrating an EUV polar jet evolving into a polar plume with a time delay of 10–15 minutes.

Spatial locations of the X-ray jets on April 7 and 8 are marked by plus signs and crosses, respectively. No SOLIS/VSM chromospheric magnetograms were available for 2007 April 8. The solar rotation effect on the events' spatial locations has been corrected using the model by Howard et al. (1990). It is clear that most jet events, in particular those of April 7, are rooted in or near magnetic flux concentrations. At the base of bright jets are relatively large flux elements of one polarity surrounded by more diffuse flux of the opposite polarity (see Figs. 2 and 3). Weaker and short-lived jets are based in areas of more diffuse magnetic flux.

Top panels of Figures 3 and 4 show a sample of nine X-ray jets recorded by *Hinode*/XRT on 2007 April 7 and 8, respectively. The different events are indexed xj$_i$ ($i = 1, \dots, 9$) according to the time of their appearance. Although the brevity of the polar observation sequences did not allow us to determine the real lifetime of several events, jet lifetimes are estimated to range from minutes to a few tens of minutes with a number of events recurring within an hour, such as event xj$_1$.

The middle and bottom panels of Figures 3 and 4 display EUV images of the southern polar region corresponding to the X-ray observations. The data cover time intervals spreading over several hours after the disappearance of the X-ray events. A number of X-ray jet events are also present in EUV images (i.e., xj$_1$ and xj$_2$ in Fig. 3*a* and the corresponding EUV structure in Fig. 3*d*; similarly xj$_7$ in Fig. 4*a* and Figs. 4*g* and 4*h*). Some of these events look brighter and sharper in EUV than in X-ray (see xj$_2$ in Fig. 3*a* and its EUV counterpart in Fig. 3*d*), perhaps for plasma temperature reasons. This highlights that X-ray and EUV jet events are contiguous when plasma conditions allow emission in both temperature ranges.

The EUV data show that a significant number of polar jet eruptions are followed by rising polar plume haze with a time delay ranging from minutes to hours. Table 1 summarizes the correlation and corresponding figures between the different X-ray and EUV events. A good example of plume haze appearing after a jet is given by the event xj$_6$, where collimated plasma emission is observed both in X-ray and in EUV images (see Fig. 4). The xj$_6$ event first appeared in X-ray images earlier than 21:31 UT (no X-ray data are available to determine the exact start time). This event dimmed around 21:47 UT and reappeared again around 21:58 UT. The collimated EUV emission lasted longer than the X-ray one and evolved gradually into a wider and hazy structure that lasted for several hours, showing a polar plume with time-varying emission. Events xj$_3$, xj$_4$, and xj$_8$ were adjacent to off-limb plume emission locations. Cases of polar jets erupting within the base of ongoing plumes resulted in emission enhancement of the latter (compare P$_{07}$ in Figs. 3*f* and 3*h* and Fig. 3*i* and P$_{08}$ in Figs. 4*d*–4*i*).

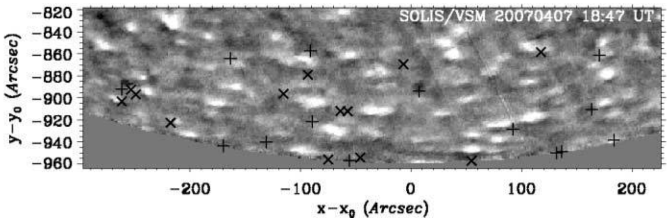

FIG. 2.—SOLIS/VSM line-of-sight chromospheric magnetogram (Ca II 8542 Å) showing the location of the X-ray jets observed by *Hinode*/XRT on 2007 April 7 (*plus signs*) and 8 (*crosses*). Their displacement due to solar differential rotation is taken into account.

4. DISCUSSION

X-ray and EUV observations indicate that more than 90% of the jets observed in the southern polar hole on 2007 April 7–8 are associated with plume haze. A total of 70% of these jets are followed by polar plumes with a time delay ranging from minutes to tens of minutes. Emission of preexisting plumes is enhanced after every jet eruption within their base. A number of prominent plumes (e.g., P$_{07}$ and P$_{08}$) show evidence for short-lived, jetlike events in the EUV that occur within the plume base (see the sharp structures in Figs. 3*f* and 3*h* and the several bright points in Fig. 3*i*). Jetlike events ensure the continuous rise of haze and may contribute to the change in plume brightness (see DeForest et al. 1997).

The event xj$_7$ in Figure 4 is an interesting case. It was observed in X-rays from 21:58 to 22:16 UT on 2007 April 8. Figures 4*d* and 4*e* shows an EUV collimated structure similar to the one observed in X-rays more than 3 hr earlier. This may be caused by the plasma being heated to several MK and then becoming visible in X-rays, then gradually cooling down until it appears in the EUV range. More data need to be analyzed to confirm the plausibility of this hypothesis.

The event xj$_9$, illustrated by Figure 4*c*, is also peculiar and lasted less than 30 minutes. A narrow, collimated beam of plasma rose from the left edge of the large bright point with a shape typical of X-ray jets. It evolved rapidly, and after 4–5 minutes the base width of the emission began to widen to cover the whole bright point. The width of the emitting structure exceeded 20 Mm, which is the typical width of polar plumes

TABLE 1

CORRELATION OF X-RAY JETS TO THE EUV JET PLUME EVENTS SHOWN IN FIGURES 3 AND 4

X-Ray Jet	EUV Jet	Polar Plume
xj$_1$ (Figure 3*a*)	Figure 3*d*	Figures 3*e*–3*i*
xj$_2$ (Figure 3*a*)	Figure 3*d*	Figures 3*e* and 3*f*
xj$_5$ (Figure 3*c*)	…	Figure 3*g*
xj$_6$ (Figures 4*a*–4*c*)	Figure 4*d*	Figures 4*e*–4*i*
xj$_7$ (Figure 4*a*)	…	Figures 4*g*–4*i*
xj$_9$ (Figure 4*c*)	…	Figures 4*g*–4*i*

NOTE.—Events close to the limb (i.e., xj$_3$, xj$_4$, and xj$_8$) are not listed.

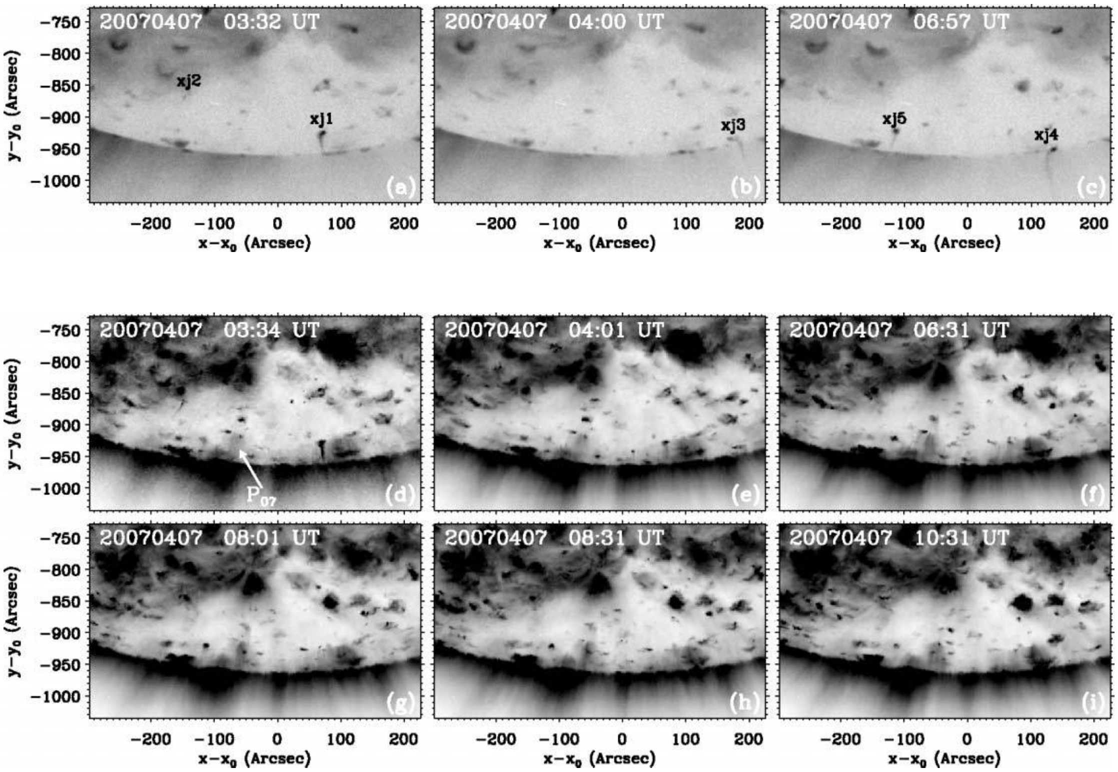

FIG. 3.—*Top: Hinode*/XRT snapshots of the southern polar coronal hole recorded on 2007 April 7 showing several X-ray jet events. X-ray jets are labeled by xj_i ($i = 1, \ldots, 5$) according to their time of appearance. *Middle and bottom:* 171 Å images from *STEREO*/SECCHI/EUVI "A" of the southern polar hole of the same day. Polar plume haze clearly rises from the same locations as X-ray and EUV jets with a time delay ranging from minutes to hours. A number of short-lived, jetlike events also occur at the base of polar plumes.

(see Wilhelm 2006). EUV images showed a faint haze several hours after the X-ray event (see Figs. 4*d*–4*i*). GONG magnetograms show that the flux at the base of xj_9 weakened during the event's lifetime. We believe that the initial jet event evolved into a plume due to significant emerging magnetic flux causing a catastrophic magnetic reconnection on a relatively short timescale but over a large spatial area. This may allow dissipation of the magnetic energy budget of the structure over a short period of time with an associated ejection of a significant amount of material over a relative large spatial scale, unlike other jet-plume events that develop over intervals of several hours. This type of event is recorded twice in the data set utilized here.

It is likely that jets play a key role in the formation process of polar plumes. Both coronal structures share numerous common characteristics, i.e., a magnetic field of mixed polarities at the base, leading to magnetic reconnection. We believe that the magnetic flux emergence causes the jet, and opening of previously closed flux results in a plume. Jet eruption seems to be the result of gradually emerging magnetic flux from the solar interior that suddenly reconnects on a small scale with the ambient photospheric field, leading to a collimated beam of plasma rising in the corona (e.g., Yokoyama & Shibata 1995). EUV images show that coronal plume haze is observed following the jet events. They also provide evidence for several small bright points and short-lived, jetlike events within the base of the plume. These may be the results of magnetic reconnection at smaller spatiotemporal scales that modulate and sporadically brighten preexisting polar plumes. This is most often seen in long-lived polar plumes, since several phases of reconnection can develop in a single long-lived structure. However, fast opening of magnetic flux can allow a plume to develop almost immediately, such as in the case of the xj_9 event.

The transition from fast, impulsive, magnetically driven dynamics of reconnection to the thermal expansion of newly liberated gas along an opened magnetic field could explain the time delay observed between the jet and plume events. On the one hand, the jet eruption is the result of fast and explosive dissipation of magnetic energy on a short timescale. On the other hand, the plume might be the result of a pressure gradient within the open flux, which would lift the plume material in the corona. This hypothesis is supported by the fact that plasma outflow velocities in plumes are measured to be rather low up to $\sim 1\ R_\odot$ above the solar surface. The continuous emergence of magnetic flux at a slow rate and relatively large scale might ultimately create a sizable bundle of newly opened flux, allowing in turn a significant plume of escaping plasma to develop.

It is beyond us to simulate the development of a jet into a plume in an MHD model. However, some basic physics of such a development can be anticipated. If a bipolar field emerges into a unipolar, open-field region, then the two fields are not, in general, exactly parallel across the boundary between them. Then, according to Parker's (1994) theory, a magnetic tangential discontinuity forms and current dissipation and field reconnection become inevitable at this boundary. Any two nonparallel fields can be resolved into parallel and antiparallel components. The antiparallel components will mutually annihilate at the discontinuity. The dissipated magnetic energy is partially converted to kinetic and thermal energy, which would cause a jet of energized plasma to escape along the open field next to the dissipating current sheet. Whenever some quantity

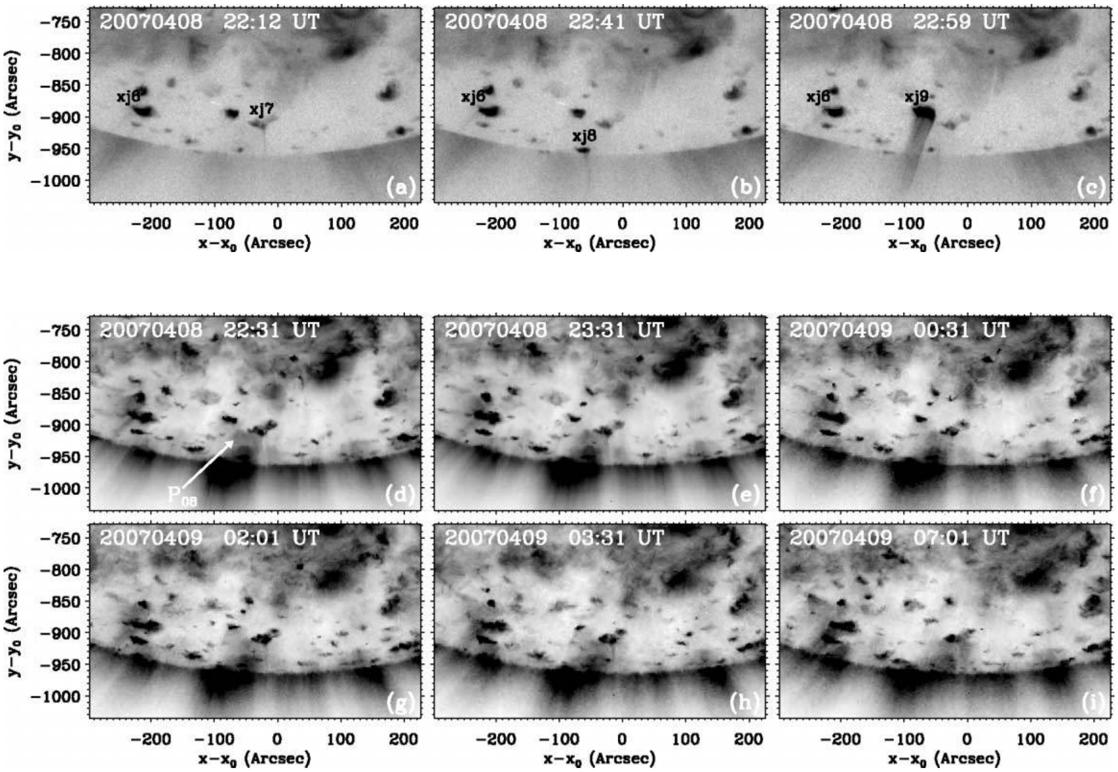

FIG. 4.—Same as Fig. 3, but for 2007 April 8. EUV images are recorded on 2007 April 8 and 9.

of open flux is locally annihilated along the current sheet, an equal quantity of closed flux must become open for magnetic flux continuity ($\nabla \cdot \boldsymbol{B} = 0$). This open flux can allow a plume of thermally expanding plasma, formerly trapped by its closed field, to escape.

A jet model with a single magnetic neutral point such as Yokoyama & Shibata's (1996) anenome jet model (see their Fig. 1) could also result in a plume. Energy gained from emerging flux is converted to kinetic and thermal energy at the X-type neutral point during reconnection, producing a jet of energized plasma. When the field has reconnected, there is a bundle of newly opened magnetic flux through which hitherto trapped coronal plasma can escape as a plume.

The present results would benefit from future, more extensive analysis of larger data samples recorded by different instruments in a simultaneous fashion over large time intervals.

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