CHROMOSPHERIC JET AND GROWING “LOOP” OBSERVED BY HINODE: NEW EVIDENCE OF FAN–SPINE MAGNETIC TOPOLOGY RESULTING FROM FLUX EMERGENCE

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ABSTRACT

We present observations of a chromospheric jet and growing “loop” system that show new evidence of a fan–spine topology resulting from magnetic flux emergence. This event, occurring in an equatorial coronal hole on 2007 February 9, was observed by the Hinode Solar Optical Telescope in the Ca II H line in unprecedented detail. The predecessor of the jet is a bundle of fine material threads that extend above the chromosphere and appear to rotate about the bundle axis at ∼50 km s−1 (period ≲200 s). These rotations or transverse oscillations propagate upward at velocities up to 786 km s−1. The bundle first slowly and then rapidly swings up, with the transition occurring at the onset of an A4.9 flare. A loop expands simultaneously in these two phases (velocity: 16−135 km s−1). Near the peak of the flare, the loop appears to rupture; simultaneous upward ejecta and mass downflows faster than free-fall appear in one of the loop legs. The material bundle then swings back in a whip-like manner and develops into a collimated jet, which is orientated along the inferred open-field lines with transverse oscillations continuing at slower rates. Some material falls back along smooth streamlines, showing no more oscillations. At low altitudes, the streamlines bifurcate at presumably a magnetic null point and bypass an inferred dome, depicting an inverted-Y geometry. These streamlines closely match in space the late Ca II H loop and X-ray flare loop. These observations are consistent with the model that flux emergence in an open-field region leads to magnetic reconnection, forming a jet and fan–spine topology. We propose that the material bundle and collimated jet represent the outer spine in quasi-static and eruptive stages, respectively, and the growing loop is a two-dimensional projection of the three-dimensional fan surface.

Key words: Sun: activity – Sun: chromosphere – Sun: flares – Sun: magnetic topology

Online-only material: color figures, animations

1. INTRODUCTION

Due to magnetic buoyancy (Parker 1955), magnetic flux ropes are expected to emerge from the convection zone into the corona through the photosphere and chromosphere. Such emerging flux regions (EFRs; Waldmeier 1937; Ellison 1944) give birth to sunspots and active regions (ARs; Weart & Zirin 1969). When observed on the solar disk, an EFR is usually seen as a new bipole of opposite magnetic polarities with regular magnetic reversals (Bruzek 1969; Roberts 1970). Such velocities of 1−5 km s−1 are typical at typical altitudes of chromosphere, driven by its magnetic pressure, but the emerging flux expands at relatively larger velocities of 10−20 km s−1, as observed in rising Hα arch filaments (Bruzek 1967; Chou & Wang 1987). Upflows of ∼1 km s−1 at the photospheric level were observed (Brants 1985) and confirmed in recent MHD simulations (Archontis et al. 2004; Martínez-Sykora et al. 2009). Once in the low-β corona, driven by its magnetic pressure, the emerging flux expands at relatively larger velocities of 10−20 km s−1, as observed in rising Hα arch filaments (Bruzek 1967; Chou & Wang 1987) and extreme ultraviolet (EUV) loops (Yashiro & Shibata 2000) in EFRs. Dense photospheric or chromospheric material dredged up by the emerging flux was found to consequentially drain down the legs of arch filaments at 30−50 km s−1 (Bruzek 1969; Roberts 1970). Such velocities of rise and drainage have been reproduced in MHD simulations (Archontis et al. 2004; Fan 2009).

When a flux rope emerges into an open-field region (e.g., coronal hole), magnetic reconnection between the emerging and ambient fields is expected to take place, producing a flare and material ejection (Heyvaerts et al. 1977). Such ejections were observed as surges in Hα (Newton 1934; Roy 1973; Kurokawa & Kawai 1993) and as jets at other wavelengths, including white light (Wang et al. 1998), UV (Brueckner & Bartoe 1983), EUV (Alexander & Fletcher 1999), and soft X-rays (SXR; Shibata et al. 1992; Strong et al. 1992). A classification of standard and blowout jets was recently proposed (Moore et al. 2010). Torsional motions or helical features found in surges or jets (Xu et al. 1984; Kurokawa et al. 1987; Shimojo et al. 1996; Patsourakos et al. 2008) were interpreted as relaxation of twists from the emerging flux (Shibata & Uchida 1986; Canfield et al. 1996; Jibben & Canfield 2004). Numerical simulations have been extensively employed to explain various aspects of solar jets (Shibata & Uchida 1985; Yokoyama & Shibata 1995; Galsgaard et al. 2005; Nishizuka et al. 2008; Ding et al. 2010).

The simplest end state of flux emergence into a (locally) unipolar region is a fan–spine configuration (Lau & Finn 1990; Török et al. 2009; cf. multiple nulls connected by separators, Maclean et al. 2009). As shown in Figure 1, consider a sufficiently small bipole emerging into a region of a larger scale that has a net, say, negative flux. The emerged flux introduces two new patches of opposite polarities, with the positive patch ending up as a minority polarity isolated in a negative polarity all around. Regardless of reconnection development, none of the field lines from this minority patch can leave this region, because the larger, surrounding region has a net opposite flux, and thus these field lines must fountain back to the nearby photosphere. Immediately outside of this closed field is the open field, and a dome or separatrix fan surface lies in between. A magnetic null point is located on the top of this dome. A special open-field line, the separatrix spine, passes through this null point to
null point

outer spine

fan surface (dome)\n
(a) inner spine

emerged flux

reconnected flux

null point

spine

Figure 1. Fan–spine topology resulting from emergence of a bipole into a unipolar region: (a) two-dimensional vertical cut; (b) three-dimensional bird’s eye view. The hatched region in (a) represents postulated bright emission (see Section 4). (A color version of this figure is available in the online journal.)

Table 1

| Event Milestones | Time (UTC)   |
|------------------|--------------|
| 02:14–02:30      | Earlier, brief surge-like activity |
| 02:32            | Bundle of material thread appears |
| 02:44            | Ca loop and overarching SXR loop appear |
| 02:49:02 (t₁)    | Onset of flare and of fast rise of material bundle and Ca loop |
| 02:50:32 (t₂)    | End of Ca loop lateral expansion |
| 02:51:12 (t₃)    | Material bundle’s lower end turns from vertical rise to horizontal drift; Ca loop “ruptures” (apex undetectable) |
| 02:51:44 (t₄)    | Elbow appears in material bundle; Northern Ca loop leg retreats downward |
| 02:52:24         | Material bundle apex starts to sweep northward |
| 02:52:40 (t₅)    | Orientation angle of material bundle axis reaches maximum near flare peak; simultaneous upward ejecta and downflow in northern Ca loop leg |
| 02:55            | Ca loop leg and overarching SXR loop invisible |

The launch of the Hinode mission (Kosugi et al. 2007) has offered new opportunities to study the relationship and underlying physics of flux emergence, jets, and fan–spine topology in unprecedented detail (e.g.; Li et al. 2007; Shibata et al. 2007; Okamoto et al. 2008; Morita et al. 2010). In an earlier Letter (Liu et al. 2009b, hereafter Paper I), we reported an intriguing chromospheric jet observed by Hinode on 2007 February 9 and focused on the fine structure kinematics of the jet itself. In this paper, we present a multiwavelength study of the entire event in greater detail. In Section 2, we provide context observations, infer the unipolar magnetic environment, and investigate the associated flare. In Section 3, we pay special attention to the material bundle as the predecessor of the jet, the accompanying growing loop system, and the inverted-Y-shaped geometry suggested by the streamlines of falling jet material.

In Section 4, we propose that flux emergence in the unipolar region gives rise to the formation of a fan–spine topology, in which we identify the observed material bundle and jet as the outer spine and the growing loop as a two-dimensional projection of the three-dimensional fan surface. We conclude...
2. MULTIWAVELENGTH CONTEXT OBSERVATIONS

The event of interest occurred on the west limb near the equator at S03W89 from 02:14 to 04:20 UT on 2007 February 9. This region was active in producing jets, including one at 13:20 UT on the same day (Nishizuka et al. 2008). The jet under study was observed by the Hinode Solar Optical Telescope (SOT; Tsuneta et al. 2008; Suematsu et al. 2008) in the Ca\textsc{ii} H line, at a 0′′.2 spatial resolution and 8 s cadence. It was also detected in H\alpha by the Yunnan Astronomical Observatory (YNAO; see Figure 2(a)) and a few other ground-based facilities, in EUV by TRACE (Handy et al. 1999), Solar and Heliospheric Observatory (SOHO) EIT, and STEREO EUV Imager (EUVI; Wuelser et al. 2004, Figures 2(b)–(f)), and in SXR by the Hinode X-ray telescope (XRT; Golub et al. 2007). RHESSI (Lin et al. 2002) and XRT also observed the accompanying GOES A4.9 flare in X-rays. The procedure of Hinode SOT data reduction can be found in Paper I and details of coaligning images from various instruments are provided in Appendix A.

2.1. Overview of Ca\textsc{ii} H, EUV, and X-ray Observations

Figures 3 and 4 show the evolution of the jet in the Ca\textsc{ii} H line, EUV, and X-rays, and Table 1 summarizes the event time line. Early in the event, from 02:14 to 02:30 UT, there is brief surge-like activity near the limb (Figure 3(a)) and tumbling motions are seen around its base at spicule heights. At the same location, a bundle of material threads of typical width ≲1′′ appears at 02:32 UT (see online Animation 1, Figure 3(b)). This bundle, as the direct predecessor of the later jet, extends above the chromosphere at an oblique angle toward the north and gradually swings up clockwise, seemingly unfolding itself and exhibiting oscillatory transverse motions across its axis. At the base of the bundle, a loop becomes visible at 02:44 UT and starts to expand both vertically and laterally (mainly toward the north). From 02:46 to 02:48 UT, blobs of bright emission are seen to swirl up in a helical-like trajectory from the chromosphere into the bundle (Figures 3(c) and (d)). Most of these can also be seen in TRACE 195 Å images (green panels in Figure 4) at lower resolution (1′′ versus 0′′.2 of SOT) as dark features, because the Ca\textsc{ii} H line emission originates from partially ionized plasma at chromospheric temperatures (≤2 × 10^4 K;
Figure 4. Nearly simultaneous images obtained by Hinode SOT in the Ca ii H line (left), TRACE at 195 Å (middle), and Hinode XRT in SXR with the Al-poly or Al-poly+Ti-poly filter (right). The Hinode images had exposure time on the order of 1 s, while TRACE had long exposures as labeled. The contours at times (f)–(h) are RHESSI 3–6 keV images with 100 s integration centered at the corresponding XRT time. The boxes in panel (f) mark the regions for integrating source fluxes shown in Figure 7(a).

(A color version and an animation of this figure are available in the online journal.)

Figure 5. PFSS model (Schrijver & DeRosa 2003) at 00:04 UT on 2007 February 9, taken 3 hr before the jet. Each panel shows the global line-of-sight magnetogram and the field lines in the vicinity of the jet, as if they were seen from the Earth at the labeled time according to the Carrington rotation. Pink lines represent the open field of negative polarity, while dark lines are of the closed field. The cross sign is the same as that in Figure 3(h), marking the central position of the Ca ii H flare.

(A color version of this figure is available in the online journal.)
Figure 6. Open-field lines of the PFSS model (as shown in Figure 5) overlaid on (a) the SOT image from Figure 4(k) and (b) the STEREO Ahead 304 Å image from Figure 2(e). The field lines were projected according to the positions of the corresponding spacecraft at the times of the images. The cross sign in (a) is the same as that in Figure 3(h).

(A color version of this figure is available in the online journal.)

Gouttebroze et al. (1997) that absorbs the background 195 Å emission from hot plasma at coronal temperatures ($\sim 1.5$ MK). Some of these absorption features can be seen in X-rays as well (e.g., Figure 4(f)).

Around 02:48–02:49 UT, the swing and rise of the material bundle and the expansion of the loop start to accelerate. At the same time ($t_1 = 02:49:02$ UT), the A4.9 flare sets in near the lower southern leg of the loop. It appears as bright emission in the Ca\textsc{ii} H line (Figure 3), EUV, and X-rays (Figure 4). At $t_2 = 02:50:32$ UT, the loop legs stop their lateral expansion, and soon after ($t_3 = 02:51:12$ UT), the loop appears to rupture and its apex becomes undetectable (Figures 3(f)–(h)). At $t_5 = 02:52:40$ UT, the angle between the axis of the material bundle and the limb reaches its maximum. The bundle then starts to sweep back toward the north in a whip-like manner and rapidly develops into a collimated jet, which eventually extends to a length of 203 Mm or 0.29 $R_\odot$ (Figure 2(e)). The loop continues to "collapse" and material is seen to drain down the northern leg toward a flare kernel only $\sim 15''$ away from the southern leg (Figures 3(i) and (j)). This indicates that the lateral expansion of the loop occurs only in the corona, while the footpoints of the loop remain anchored on the surface.

The jet material is seen as emission in the cool ($\sim 10^4$ K) Ca\textsc{ii} H and H\alpha lines and at 304 Å ($\sim 10^5$ K) and 171 Å ($\sim 1$ MK), as absorption in the hotter ($\sim 2$ MK) 284 Å line (Figure 2), as multiple strands of absorption and emission at intermediate ($\sim 1.5$ MK) 195 Å (Figure 4), and as weak emission in XRT SXR ($\sim 1–30$ MK; Figure 4(g)). This indicates a wide range of temperatures, from $10^4$ to $10^6$ K, in the jet plasma.

The jet exhibits oscillatory transverse motions across its axis as seen by SOT, which we interpreted in Paper I as spins resulting from unwinding twists. Further evidence of this interpretation is found at 195 Å here, where the emission and absorption strands alternate and shadow each other in sequence, as expected for a spinning cylinder in a side view (see online Animation 2).

Later in the event, a flare loop appears in SXR and then EUV (Figure 4). Part of the jet material that fails to escape the gravitational bound returns to the chromosphere along smooth streamlines in the original direction of ascent (Figure 2(f)). The oscillatory transverse motions seen earlier in the jet are no longer present in the falling material (see Figures 1 and 3 in Paper I). At lower altitudes, most of the streamlines bypass a dome-shaped region and outline an inverted-Y geometry (Figure 3(k)).

2.2. Magnetic Environment: Local Coronal Hole

This event occurred near the limb and thus there was no reliable direct magnetic field measurement available. We then resorted to the potential field source surface (PFSS) model (Zhao & Hoeksema 1994; Schrijver & DeRosa 2003) available in the SolarSoft package to obtain indirect information of the magnetic topology in the vicinity of the jet. The modeled field is the extrapolation of a photospheric magnetogram that combines SOHO Michelson Doppler Imager observations within 60° of the disk center and the evolved fields elsewhere according to the flux disperse model.

Figure 5 shows the PFSS model field at 00:04 UT near the time of the event, as seen from different view angles. We noticed a north–south oriented narrow channel (range: 6° in longitude, 18° in latitude) of an open field or a coronal hole located between two NOAA ARs 10940 and 10941. The models up to 7 days prior to the event show that this coronal hole persistently existed, evolved slowly in size and shape, and matched the dark regions seen in SOHO EIT 284 Å images as expected. We then rotated the 00:04 UT model field to the time of the jet according to the Carrington rotation rate and found that the event was located inside the coronal hole. An example is shown in Figure 3(h),

4 See the model predicted coronal hole boundaries at
http://www.lmsal.com/isolsearch and their overlays on EIT images at
http://lmsal.com/forecast/modelEUV.
where the coronal hole boundary (dotted line) encompasses the kernels of the flare. This is consistent with the finding of Nitta et al. (2008) for an AR jet and with the expectation that coronal jets tend to occur in open-field regions, as manifested by the ubiquitous polar jets observed by Hinode (Cirtain et al. 2007; Shibata et al. 2007). Close comparison with the PFSS model further indicates that the northwest orientation of the jet is close to those of the open-field lines, again as expected from classical jet models. This can be clearly seen in both SOT Ca ii images (Figure 6).

2.3. Associated Microflare

The accompanying A4.9 flare occurred at 02:49 UT and peaked at 02:53 UT in the GOES low channel (1–8 Å) flux. As can be seen in Figures 7(a)–(c), the light curves in the Ca ii H line (SOT) and X-rays (GOES and RHESSI) are very similar, showing a single hump, except for slightly different onset and peak times, presumably due to different instrument response to the varying plasma temperature. The TRACE EUV light curve shows a different trend except during the rise of the flare. The initial decrease from 02:37 to 02:47 UT is due to the unfolding material bundle and growing loop at chromospheric temperatures, which lead to increased absorption of the background EUV emission. The second flux increase (02:56–03:01 UT) is likely the result of the hot X-ray emitting plasma cooling to 195 Å passband temperatures and/or continuous evaporation of chromospheric plasma due to thermal conduction (Zarro & Lemen 1988; Battaglia et al. 2009; Liu et al. 2009d).

The flare emission appears near the lower southern leg of the loop and cospatial at various wavelengths, from Ca ii H to EUV and X-rays (Figures 3 and 4). It is seen by RHESSI up to the 6–12 keV band. Fits to RHESSI spectra at the flare peak indicate that the emission is primarily thermal bremsstrahlung from a plasma of temperature \( T = 12.2 \pm 0.6 \text{ MK} \) and emission measure \( EM = (5.5 \pm 0.5) \times 10^{45} \text{ cm}^{-3} \) (see Appendix B). As shown in Figures 7(d) and (e), \( T \) and \( EM \) have simple temporal profiles. Their differences between GOES and RHESSI likely result from the well-known fact that GOES is more sensitive to cooler plasmas. Note that, because of their sharp occultation at the chromospheric limb, the three bright loops seen earlier by XRT (Figure 4(a)) are most likely located behind the limb. The flare loop happens to be in front of the background loop in the middle (\( y \sim -40'' \)) and is located on the visible side of the disk, since its footpoints are inside the limb (Figure 4(l)) and the flare kernels are clearly observed (Figure 3(j)).

3. HINODE SOT DATA ANALYSIS

In this section, we make geometric measurements of various features projected onto the sky plane observed by Hinode SOT in the Ca ii H line. Bear in mind that projection effects may limit our capability of uncovering the true three-dimensional picture. Here we assume that the displacements of Ca emission features represent motions of material rather than sequential excitations of emission due to temperature or density variations (see Appendix C).

3.1. Material Bundle: Jet Predecessor and Early Development

As briefly mentioned in Section 2.1, the predecessor of the jet is a bundle of material threads that exhibits transverse motions across its axis. To quantify these motions, we have placed six 3'' wide cuts along the bundle, oriented roughly perpendicular to the local threads as shown in Figure 3(b). Spacetime diagrams
The apex, lower end, and axis as marked in Figure 3(e). The apex signs on the left in Figure 8, which exhibit a delay from one journal.

(A color version and an animation of this figure are available in the online journal.)

We find a slow-to-fast two-phase evolution\(^6\) clearly divided by the onset of the accompanying flare at \(t_1 = 02:49:02\) UT. (1) Prior to \(t_1\), the apex height \(\Delta h_{\text{bdl}}\), axis angle \(\theta_{\text{bdl}}\), and displacements of the bundle’s lower end from its initial position \((\Delta x_{\text{bdl}}, \Delta y_{\text{bdl}})\) show slow variations (Figures 10(b)–(d)). The clockwise upward swing of the axis is evident in the increase of \(\theta_{\text{bdl}}\) at a moderate velocity of \(\dot{\theta}_{\text{bdl}} = (4.9 \pm 0.2) \times 10^{-2} \text{ deg s}^{-1}\). (2) At the flare onset, all of these quantities but \(\Delta h_{\text{bdl}}\) start to increase rapidly. \(\dot{\theta}_{\text{bdl}}\) experiences an acceleration and reaches \((3.1 \pm 0.2) \times 10^{-2} \text{ deg s}^{-1}\) at \(t_3 = 02:52:40\) UT when its growth comes to a stop followed by a reversal. Overall, \(\dot{\theta}_{\text{bdl}}\) has gained more than 50\(^\circ\) in 10 minutes. The bundle’s lower end first moves mainly upward \((\Delta x_{\text{bdl}})\) with a velocity of \(0.66 \pm 0.09 \text{ km s}^{-2}\). \(\Delta h_{\text{bdl}}, \Delta x_{\text{bdl}}, \Delta y_{\text{bdl}}\), and \(\theta_{\text{bdl}}\) start to increase \((3.1 \pm 0.2) \times 10^{-2} \text{ deg s}^{-1}\) at \(t_3 = 02:52:40\) UT when its growth comes to a stop followed by a reversal. Overall, \(\dot{\theta}_{\text{bdl}}\) has gained more than 50\(^\circ\) in 10 minutes. The bundle’s lower end first moves mainly upward \((\Delta x_{\text{bdl}})\) with a velocity of \(0.66 \pm 0.09 \text{ km s}^{-2}\). \(\Delta h_{\text{bdl}}, \Delta x_{\text{bdl}}, \Delta y_{\text{bdl}}\), and \(\theta_{\text{bdl}}\) start to increase \((3.1 \pm 0.2) \times 10^{-2} \text{ deg s}^{-1}\) at \(t_3 = 02:52:40\) UT when its growth comes to a stop followed by a reversal. Overall, \(\dot{\theta}_{\text{bdl}}\) has gained more than 50\(^\circ\) in 10 minutes. The bundle’s lower end first moves mainly upward \((\Delta x_{\text{bdl}})\) with a velocity of \(0.66 \pm 0.09 \text{ km s}^{-2}\). \(\Delta h_{\text{bdl}}, \Delta x_{\text{bdl}}, \Delta y_{\text{bdl}}\), and \(\theta_{\text{bdl}}\) start to increase \((3.1 \pm 0.2) \times 10^{-2} \text{ deg s}^{-1}\) at \(t_3 = 02:52:40\) UT when its growth comes to a stop followed by a reversal. Overall, \(\dot{\theta}_{\text{bdl}}\) has gained more than 50\(^\circ\) in 10 minutes. The bundle’s lower end first moves mainly upward \((\Delta x_{\text{bdl}})\) with a velocity of \(0.66 \pm 0.09 \text{ km s}^{-2}\). \\

\(^6\) Similar phases of slow and fast rises have also been reported in other eruptive events, including coronal jets (Patsourakos et al. 2008) and prominence eruptions (Sterling & Moore 2005; Chifor et al. 2006; Liu et al. 2009c).

\(^7\) The bundle’s apex height does not appear to increase monotonically, because of the jumps caused by changes in brightness and thus switches of the feature to be tracked (Figure 10(b)).

Figure 9. Same as Figure 8(d) but with an enlarged view and slightly different color scale to emphasize oscillatory tracks. Overlaid are sinusoidal fits (thick dotted line) to selected tracks, and listed nearby are the fitted parameters: amplitude \(A\), period \(P\), and velocity \(v_1\), at the equilibrium position marked by the dot-dashed line.

(A color version of this figure is available in the online journal.)

Figure 10. Same as Figure 8(d) but with an enlarged view and slightly different color scale to emphasize oscillatory tracks. Overlaid are sinusoidal fits (thick dotted line) to selected tracks, and listed nearby are the fitted parameters: amplitude \(A\), period \(P\), and velocity \(v_1\), at the equilibrium position marked by the dot-dashed line.

(A color version of this figure is available in the online journal.)

Figure 8. Spacetime plot of cuts perpendicular to the local threads of the material bundle as shown in Figure 3(b). The plus signs indicate the times of the crest of a sinusoidal oscillation, and the crosses mark the onsets of the rapid rise of the bundle, both indicating a delay at higher cuts. The vertical positions of the symbols are scaled with the separations of the corresponding cuts and are fitted with the dotted lines (see the text) labeled by their final velocities. (See the original images overlaid with the cuts in the online animation.)

(A color version and an animation of this figure are available in the online journal.)

3.2. Accompanying Growing Loop

Another key component of this event is the growing \(\text{Ca}^{II}\) H loop that accompanies the rise and eruption of the material bundle. We track the evolution of its apex height \(h_{\text{loop}}\) and the lateral span of its two legs (see Figure 3(e)). The latter is derived from the solar-\(y\)-coordinates of the legs’ outer edges since the \(y\)-axis here near the equator is almost parallel to the limb.

Similar to the material bundle, the loop apex also experiences two distinct phases divided at the flare onset \(t_1\) (Figure 10(e)): (1) a gradual phase from 02:44 to \(t_1\) with a moderate ascent velocity of \(16.2 \pm 0.4 \text{ km s}^{-1}\) and (2) an acceleration phase from \(t_1\) to \(t_3 = 02:51:12\) UT with an acceleration of \(0.73 \pm 0.06 \text{ km s}^{-2}\) and a final velocity of \(135 \pm 4 \text{ km s}^{-1}\). The second phase ends when the loop appears to rupture and its apex is no longer visible. This
coincides with the turning point of the material bundle’s lower end mentioned above (Figure 10(d)).

The lateral position $y_{N\text{Leg}}$ of the northern leg of the loop has a similar two-phase evolution with 1–2 times larger velocities and acceleration (Figure 10(f)). In contrast, the southern leg does not show such a distinction and has a uniform low velocity of $-5.2 \pm 0.1$ km s$^{-1}$, only one-fourth of its northern counterpart $(23.3 \pm 0.7$ km s$^{-1}$) in the gradual phase. This asymmetry means that the lateral expansion of the loop is primarily on the northern leg moving toward the north. Note that the lateral expansion velocity and acceleration averaged between the two legs roughly equal their vertical counterparts. The lateral expansion, however, ceases earlier than the vertical growth. This occurs in both legs at $t_2 = 02:50:32$ UT $< t_3$, after which they remain stationary with small fluctuations (standard deviation: 0’4).

To examine the shape of the loop, we define the aspect ratio of the loop apex height to the half separation of the two legs in the north–south direction, $R \equiv h_{\text{loop}}/[(y_{N\text{Leg}} - y_{S\text{Leg}})/2]$. As shown in Figure 10(g), this ratio has a mean of 2.2 $> 1$, indicating vertical elongation. The elongation is reduced with $R$ decreasing from $\sim 3.2$ to 1.8 during the gradual expansion phase (02:44 UT–$t_1$). The loop then preserves its shape with a constant aspect ratio $\sim 1.8$ during the common acceleration phase ($t_1$–$t_2$), but the elongation slightly increases afterward because of the earlier cessation of the lateral expansion.

Near the end of the visible lifetime of the accompanying loop, the northern leg exhibits interesting behaviors. There are two branches at this leg which initially expand upward during the loop growth. When the elbow of the material bundle appears at $t_4 = 02:51:44$ UT as noted above, the two branches start to bend and retreat downward. We identified five bright blobs (A–E) as shown in Figure 11, among which blobs A and D represent the visible apexes of the two branches. We then tracked the blob locations with time (Figure 12(a)) and used blob sizes as uncertainties. For each blob, its positions are well represented by a straight line fit, which gives its main direction of motion. We obtained the distance along this direction and inferred the corresponding velocity and/or acceleration (Figures 12(b) and (c)).

We find that both blobs A and D exhibit a downward acceleration followed by a deceleration within $\sim 1$ minute, and their average velocities are nearly $-100$ km s$^{-1}$ (see Table 2). Near the onset (02:52:24 UT) of the northward sweep of the material bundle, blob A becomes too vague to be identified, while two new blobs, B and C, appear nearby. They shoot upward with an acceleration $a \sim 11$ $g_\odot$ (where $g_\odot = 0.274$ km s$^{-2}$ is the solar gravitational constant) and reach final velocities of 192 $\pm 18$ and 130 $\pm 18$ km s$^{-1}$. In contrast, as blob D slows down its downfall near $t_5 = 02:52:40$ UT, it turns its horizontal direction from the north to the south (Figure 12(a)) and we assign it a new blob ID named E. This blob resumes a downfall with an acceleration of $a = (-4.8 \pm 0.7) g_\odot$ and reaches a velocity of $-115 \pm 9$ km s$^{-1}$ just before it plunges into spicules in the chromosphere. Since the blobs are tracked by their projected two-dimensional positions in the sky plane, these velocities and accelerations are lower limits of their true values in three-dimensional space. Meanwhile, the solar gravitational acceleration $g_\odot$ is the upper

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**Table 2**

| Trajectory or Blob ID | Linear Fit (v) (km s$^{-1}$) | Parabolic Fit $a/g_\odot$ | $t_{\text{final}}$ (km s$^{-1}$) |
|-----------------------|-----------------------------|--------------------------|-----------------------------|
| A                     | $-94 \pm 5$                | ...                      | ...                        |
| B                     | $121 \pm 5$                | $11.4 \pm 3.1$           | $192 \pm 18$               |
| C                     | $58 \pm 5$                 | $11.1 \pm 2.6$           | $130 \pm 18$               |
| D                     | $-95 \pm 4$                | ...                      | ...                        |
| E                     | $-57 \pm 2$                | $-4.8 \pm 0.7$           | $-115 \pm 9$               |

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Figure 10. History of geometric quantities of the Ca II H material bundle (jet) and loop. (a) Light curves at various wavelengths repeated from Figure 7. (b) Height $h_{\text{loop}}$ of the material bundle apex. (c) Angle $\theta_{\text{loop}}$ of the material bundle axis from the horizon. (d) Solar $x$ and $y$ displacements of the lower end of the material bundle as shown in Figure 13(c). Major milestones of the event are labeled as $t_1$, $t_2$, $t_3$, $t_4$, and $t_5$ (see Table 1). (e) Height $h_{\text{loop}}$ of the loop apex. (f) Solar-$y$ coordinates of the northern and southern legs of the loop, $y_{N\text{Leg}}$ and $y_{S\text{Leg}}$. The horizontal lines starting at $t_2 = 02:50:32$ UT mark the means of the data after this time. Velocities and accelerations from linear and parabolic fits are labeled in (b)–(f). (g) Aspect ratio of the loop apex height $h_{\text{loop}}$ to the half separation of the two legs in the north–south direction, $(y_{N\text{Leg}} - y_{S\text{Leg}})/2$. (A color version of this figure is available in the online journal.)
Figure 11. Enlarged view of the northern leg of the Ca II H loop at its late stage. Note the downward retreat of branches A and D and the upward ejection of blobs B and C.

(A color version of this figure is available in the online journal.)

Figure 12. Kinematics of the emission blobs in the northern leg of the loop as marked in Figure 11. (a) Locations of blobs A–E with colors from magenta to red indicating time evolution. For each blob, a red arrow represents the main direction of motion, given by a linear fit to the data. (b) Distance along the main direction of motion for each individual blob, with positive (negative) for upward (downward). The curves are shifted vertically to make their end points approximately represent the relative heights of the corresponding blobs. (c) Time derivative of the distance in (b). The red lines in (b) are parabolic fits to curves B, C, and E, labeled with the fitted accelerations and final velocities, and their counterparts in (c) are the corresponding velocities vs. time.

(A color version of this figure is available in the online journal.)

limit of its component along the unknown three-dimensional trajectory. Thus, blob E's downward acceleration is at least fivefold greater than a corresponding free-fall (dotted line in Figures 12(b)). Its final velocity is also 2–3 times larger than those (30–50 km s$^{-1}$) found at the footpoints of H$\alpha$ arch filaments (Bruzek 1969; Roberts 1970). Even if a free-fall starts at a higher altitude at the top of trajectory D, it would reach a final velocity of only 42 km s$^{-1}$, about one-third of trajectory E's value.

3.3. Streamlines of Falling Material: Inverted-Y Geometry

As mentioned earlier, jet material bound by gravity falls back to the chromosphere and this continues throughout the duration of this event. The trajectories of the falling material are smooth streamlines, which, at altitudes $\gtrsim 20''$, are almost straight lines in the original direction of ascent. Kinematics of the falling material above this height was investigated in Paper I using spacetime plots (see Figure 2 there). Below this height, the streamlines are curved as if they bypass an unseen dome or null point. This can be clearly seen in the online Animation 1, especially from 03:25 to 03:35 UT.

To highlight these streamlines, we performed running difference between each pair of images 2 minutes apart (every 15 frames at an 8 s cadence) within a selected duration, and superimposed the positive parts of all differenced images. A sample of the results is shown in Figures 13(a)–(c). We then visually traced the streamlines, a collection of which clearly outlines an inverted-Y geometry (Figure 13(d)). By overlaying these streamlines on top of multiwavelength images (Figures 13(e)–(h)), we note the following spatial relationships: (1) some streamlines, particularly those on the right-hand side,
4. INTERPRETATION OF OBSERVATIONS

The observations presented above bear two significant implications. First, the Ca loop comes into sight on the visible side of the limb, starts to grow into the chromosphere among neighboring spicules, and makes its way into the corona, expanding vertically and laterally. This suggests that the growing loop results from the emergence of a magnetic bipole from below the photosphere. This inference is supported by the following three factors: (1) the loop’s initial upward expansion velocity of $16.2 \pm 0.4 \text{ km s}^{-1}$ is of the same order of magnitude as the 10–15 km s$^{-1}$ Doppler velocities of rising arch filaments in EFRs (Chou & Zirin 1988), as well as the $\sim 20 \text{ km s}^{-1}$ speeds of emerging flux ropes found in three-dimensional MHD simulations (Archontis et al. 2004; Fan 2009; Martínez-Sykora et al. 2009) and of recently discovered prominence plumes (Berger et al. 2008). (2) The separation ($\sim 15^\circ$) of the flare kernels (at loop footpoints) is only half of the separation between the Ca loop legs, which is expected for emerging flux due to its rapid lateral expansion in the corona. (3) In addition, it is possible that the earlier, weaker surge\(^8\) (02:14–02:30 UT) is the

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\(^8\) This earlier surge and the main jet, together with another jet occurring 10 hr later (Nishizuka et al. 2008), could be part of the recurring jet activity, which has been observed in other events (Chifor et al. 2008) and simulated with MHD models (Archontis et al. 2010; Pariat et al. 2010).
initial signature of flux emergence. If so, the 30 minutes delay of the first appearance of the Ca loop at 02:44 UT is consistent with the timescale for the emergence of a typical small-scale ephemeral region. This time is required for the emerging flux to be built up in order to generate sufficient upward pressure force and to drain heavy material carried from the interior before it can further expand into the corona.

We note that, other than flux emergence, footpoint shearing, twisting, or braiding motions of a pre-existing coronal structure, such as an arcade of coronal loops, can also increase its magnetic stress and helicity and cause it to expand or even erupt (e.g., Antiochos et al. 1999; Rachmeler et al. 2010). So we examined available data from Hinode, TRACE, and STEREO. However, we found no indication (either emission or absorption) of the prior existence of the loop or material bundle at any size resolved by the instruments (down to 0″.2) and up to 2 hr before this event. These data include multiple wavelengths—Ca II H, EUV (171, 195, 284, and 304 Å), and SXR—which cover a wide range of temperatures (10^5–10^7 K). This essentially rules out the possibility that the appearance of the Ca loop results from temperature changes and/or expansion of a pre-existing coronal structure. Hence, flux emergence still remains the most likely possibility for the origin of the Ca loop, although we have no reliable magnetograms of this near-limb region to provide direct evidence.

The second implication of our observations is that, as mentioned in Section 1, any bipolar emerging into a unipolar region, i.e., the coronal hole in this case, can naturally lead to a fan–spine topology (Antiochos 1998; Török et al. 2009). The streamlines of the falling material, assumed to be parallel to magnetic field lines, clearly indicate such a configuration as shown in Figure 1. In particular, streamlines \(a_0\) and \(b_0\) evidently bifurcate, suggesting that the spine is located between them and the null point lies close to the bifurcation. The fact that the streamlines avoid the dome indicates that the jet material originates from above the separatrix fan surface. There are, however, outliers to this general trend, and streamlines \(b_1\) and \(c_1\) apparently pass through the dome. This is likely a projection effect of the true three-dimensional geometry, in which these streamlines lie behind or in front of the dome that has a finite extent along the line of sight (e.g., Figure 1(b)).

Note that the three-dimensional fan–spine configuration has a variant form in a two-dimensional geometry with translational invariance in the third dimension or in a three-dimensional geometry with a significantly elongated parasitic polarity. In this case, the three-dimensional null point is replaced with a separator line and the spine line is replaced with a spine surface. This surface divides the volume underneath the dome into two topologically separate chambers (see Figure 3 of Moreno-Insertis et al. 2008), which are, however, a single connectivity domain in the true three-dimensional null case. The observations of flow streamlines very likely located behind or in front of the inferred dome provide a basis for our adoption of the true three-dimensional null model for our discussion in the rest of the paper.

### 4.1. Proposed Model

Based on the above two inferences, we postulate that the earlier material bundle and later collimated jet represent the outer spine and its neighboring field lines in different stages, while the growing Ca loop is a two-dimensional rendering (projection) of the entire three-dimensional dome or separatrix fan surface (Figure 1). We believe that, among alternative models, this conjecture best explains the observations. The postulated event develops as follows (see Figure 14).

When a twisted flux rope emerges into the corona in an open-field environment, the flux rope expands rapidly, driven by its considerable magnetic pressure, and presses onto the ambient field to form a current sheet at the discontinuity between them (Heyvaerts et al. 1977). Magnetic reconnection ensues and results in a fan–spine structure mentioned above. The outer spine originates from the null point and opens to infinity, while the inner spine apparently divides the vault under the dome into two parts seen in two-dimensional projection.

Reconnection outflows continuously pump dense plasma upward along the newly reconnected field lines near the outer spine. Emission from such plasma (hatched region around the spine in Figure 1(a)) could be responsible for the observed material bundle and later collimated jet, whose diffuse upper end and relatively sharp lower end (Figures 3(f)–(h)) are readily explained by the geometry of the outer spine. Reconnection also transfers magnetic helicity from the emerging flux rope into the newly reconnected open field. This and plasma pumping are both manifested in the upward swirling motion of material along the helical trajectory observed around 02:47 UT (Figures 3(c) and (d)). Under the influence of the Lorenz force, the twists in the reconnected open field tend to unwind themselves and drive these field lines to rotate, as found in spining Hz surges (Shibata & Uchida 1986; Canfield et al. 1996). Such spins propagate upward toward the open end in the form of torsional MHD waves, and their two-dimensional projections would appear as traveling sinusoidal oscillations, just as observed here (Section 3.1). The inferred rotational velocities and periods (Figure 9) are comparable to those of transverse oscillations found in X-ray jets (Cirtain et al. 2007), prominences (Okamoto et al. 2007), and coronal loops (Ofman & Wang 2008), which were interpreted as signatures of Alfvén or fast kink mode waves (Vasheghani Farahani et al. 2009). Our inferred phase speed of \(v_\phi = 786 \pm 30\ km\ s^{-1}\) is also within the range of typical coronal Alfvén or fast-mode speeds. At the same time, the Lorentz force associated with the twists and axial gradient of currents (e.g., see the current density in Figure 9 of Pariat et al. 2009) may have a strong axial component that can drive the upward ejection of material along the axis of the bundle (Bellan et al. 2005).

As the dense emerging flux rope expands and sweeps through the dense lower atmosphere ahead of it, a layer of enhanced local density is expected to form at its leading front. In our case, this layer is the fan surface between the emerging flux and the ambient open field, marked as the hatched region on the dome in Figure 1(a). In two-dimensional projection, it could appear as the growing Ca loop seen here. The expansion rate of the flux rope, presumably depending on the flux emergence rate and the interplay between the strengths of the emerging field and the surrounding field, controls the dynamic evolution. Early in the event (before \(t_1 = 02:49:02\ UT\)), the flux rope (thus the fan surface) expands at a moderate speed (16.2 ± 0.4 km s\(^{-1}\)), giving the ambient field a gentle push. This leads to moderate rates of reconnection and supply of mass and helicity to the material bundle around the spine, which evolves in a quasi-static manner. As sufficient twists have emerged into the corona with time, a kink-like instability can occur and force the flux rope to undergo an accelerating expansion (Fan & Gibson 2004; Pariat et al. 2009; Rachmeler et al. 2010), strongly pushing the ambient field and thus driving rapid reconnection. If we interpret flares to be indicators of rapid energy release by fast reconnection, we
may identify time $t_1$ as the onset of the observed flare heating in this event. In addition, the increased fluxes of mass and helicity transferred to the material bundle through reconnection can no longer relax in a quasi-static manner, eventually resulting in a runaway instability that leads to the collimated jet. This explains the simultaneous transitions from slow to fast evolution for both the material bundle and growing loop (Figure 10). This is also energetically analogous to the two regimes found by Pariat et al. (2010): slow, quasi-static reconnection in the energy-storage phase, and fast, dynamic reconnection in the energy-release phase in a rotating current sheet associated with the kinking flux under the fan surface.

Because of continuous reconnection, the material bundle around the spine is a constantly evolving entity. A given field line in the bundle is illuminated only when reconnection drives dense mass flow along it. It becomes invisible once the temperature leaves the Ca $\text{ii}$ H response range (≤2×10$^4$ K) or the density drops significantly, which could be true at high altitudes or when the reconnection site migrates away. In the former case, the material bundle would correspond to the lower portion of a jet or surge, whose upper portion has upflows at reduced density and brightness. This gives rise to the diffuse appearance of the upper end of the bundle. This also explains why the streamlines of the falling material are distributed in a large volume and in various directions (Figure 13), not just along the path of the final collimated jet. This is because material is continuously ejected upward in different directions when the bundle swings, as what happens when a fireman swings his firehose. In the latter case of reconnection site migration, the visible threads in the material bundle are constantly being replaced and we see different field lines over time as reconnection develops. This could explain why each sinusoidal oscillation (Figure 8) appears ephemeral.

As the system seeks its lowest energy state, the open-ended spine field line can change its orientation, while the null point migrates in space from field line to field line, depending on the dynamic evolution of reconnection (Figure 14). This seems to reflect what we observe here and explain the elbow (Figure 3) and the drift of the material bundle’s lower end (Figure 13(c)). The latter is likely located near the null point and its overall upward migration may result from the upward development of reconnection as predicted in the standard flare model (Sturrock 1966; Kopp & Pneuman 1976) or from a cumulative effect of advection motions driven by gas pressure in the neighborhood of the null where the Lorentz force vanishes (Pariat et al. 2009).

The low angle of the material bundle in its early stage probably reflects the strong horizontal field at low altitudes. The back-and-forth fast (151 km s$^{-1}$, see Figure 4 in Paper I) swing of the entire material bundle possibly results from catastrophic release of excessive twists into the open field, similar to the kink or writhé of a flux rope. Also, if we assume the measured twist propagation velocity 786 km s$^{-1}$ to be the Alfvén velocity $v_A$, the velocity ratio 151/786 = 0.19 is close to the 0.2 value of the drifting outer spine found in the three-dimensional simulation of Pariat et al. (2009).

4.2. Discussion

Many characteristics of our observations and the above interpretation resemble those in the simulation of Török et al. (2009), particularly their fan–spine topology with a three-dimensional null point resulting from emergence of a bipole into a locally unipolar region and the launch of a torsional MHD wave from the reconnection site. However, in their case, magnetic reconnection develops in two steps and each step leads to the formation of hot loops on each side of the spine, which constitute one-half of a full anemone, consistent with the Hinode XRT observations of a specific jet event. In our case, we found no signature of such two-step reconnection, and we could not identify the expected inner spine emission (hatched with dashed lines in Figure 1(a)) in available data, presumably due to unfavorable temperatures and/or densities under the dome. However, the flare loop in SXR and EUV (Figures 13(g) and (h)) and its right branch in Ca $\text{ii}$ H (Figure 4(h)) are located in the expected position to the right-hand side of the null point for the newly reconnected field.

We note that the upward expansion of the emerging flux toward the north has a large component parallel to the ambient field and can readily make its way in a herniation manner, while the expansion toward the south must perpendicularly press the ambient field against strong resistance. This topological asymmetry can therefore preferentially facilitate the northward expansion, which is at least four times faster than its southward counterpart (Figure 10(f)). This is similar to the simulation of the primarily vertical (versus horizontal) expansion of the dome in a vertical ambient field (Pariat et al. 2009). In addition, the null point can be more readily advected in the spine direction, as manifested in its overall upward and northward migration (Figure 13(c)).

The northern leg starts to reverse its expansion and retreat downward at $t_4$ = 02:51:44 UT. In addition, when the material bundle sweeps toward the north, its lower end, assumed to be near the null point, slightly drops in height by $3^\circ$ (Figures 10(d)). These occur near the peak of the flare, possibly when a significant amount of energy has been released. This is consistent with the implosion conjecture of Hudson (2000) and its theoretical demonstrations (Zhang & Low 2003; Janse & Low 2007). It predicts that after major energy release, the magnetic pressure (or energy density) in the local volume is significantly reduced and the resulting imbalance with the pressure in the surroundings would push this volume to contract. Observational evidence of this conjecture has gradually emerged (Liu et al. 2009a, 2009c). When this happens, opposite to an expanding twisted flux rope in which twists tend to accumulate in the expanded top portion (Parker 1979, p. 189), more twists will be pushed by the Lorentz force to concentrate in the leg portion when the rope contracts. This explains why twists become more visible in the northern leg later when it contracts. This downward Lorentz force might also provide additional push to the material and help explain the faster than free-fall downflow observed here (Figures 11 and 12).

At the same time, some material is ejected upward at accelerations up to (11.4 ± 3.1)g$\odot$ (Figures 11 and 12). It is quite puzzling for this to take place simultaneously in the same northern leg as the fast downflow, even though they might occur on different field lines at separate line-of-sight positions. In any case, there are several possible explanations which we cannot distinguish with the available data: (1) if the ejection is on twisted field lines that reconnect with untwisted open-field lines, it could be driven by the Lorentz force associated with the upward relaxation of twists, which seems to happen here (Figures 11(g)–(o)). (2) If the upward ejection and downflow are indeed on the same field lines, they could be the upward and downward branches of the secondary outflows bifurcated from the primary reconnection outflow as predicted in MHD simulations (Yokoyama & Shibata 1996; Moreno-Insertis et al. 2008). (3) Another less likely possibility is that the ejection and
downflow are oppositely directed outflows from reconnection occurring at an X-point between them. An X-type null point at this location is, however, not favored by our adoption of the spine–fan topology to interpret this event.

The disappearance of the Ca ii H loop possibly results from the combination of several processes, including mass drainage, temperature variation, and topological change. The first two mechanisms are expected to operate gradually, while the third one could happen catastrophically. First, as a flux rope emerges and plows through the lower atmospheres, dense material is dredged into the hot corona. Part of this material would contribute to the Ca emission seen at the fan surface. Such dense material is expected to be pulled back by gravity and slide down the dome, as seen in Hα arch filaments (e.g., Chou & Zirin 1988). This is because the scale height of the $\lesssim 2 \times 10^{4}$ K plasma emitting the Ca ii H line is only $\lesssim 1.2$ Mm and pressure gradient from gravitational stratification is simply too small to support the weight of plasmas extending to the height of the dome (>10 Mm). In our case, such mass loss is evident in the northern leg of the loop. This would make the apex of the dome to have the lowest density and become less well defined and then invisible first, before the loop legs gradually fade away (Figures 10(e) and (f)). Second, heating of the Ca loop (fan surface) may occur during the course of its rise, possibly as a result of reconnection with the ambient field. Once its temperature rises above the $\lesssim 2 \times 10^{4}$ K range, the Ca ii H loop would disappear. This can be seen in Figure 4(h), where the northern leg of the loop is vague in Ca but prominent and bright at 195 Å. Later, because of significant mass drainage that has considerably reduced the density of the loop (fan surface), it would no longer appear as detectable absorption or emission in EUV or SXR, as we see here (Figures 4(j) and (k)). Finally and more importantly, a catastrophic topological change, which may be involved in the launch of the chromospheric jet, can alter field connectivity and contribute to the disappearance of the fan surface in emission.

We note in passing that there is an overarching loop brightening in SXR at 02:44 UT (see Figure 4(b)) that appears simultaneously with the bright Ca ii H loop (dark in EUV) but $\sim 10^{"}$ higher in altitude. The southern leg of the Ca loop appears as dark absorption in SXR (Figure 4(f)), suggesting that the SXR loop brightening is located behind the Ca loop. When the legs of the Ca loop disappear around 02:55 UT (Figure 10(f)), this SXR loop becomes invisible too (Figure 4(j)). These timing coincidences seem to suggest that the SXR loop is of the same emerging flux system as the Ca loop but at higher altitudes and temperatures. However, during its lifetime, the SXR loop hardly changes its size or shape, while the Ca loop has risen more than 20", well beyond the XRT’s 2” spatial resolution. This contradicts the expectation that the overarching SXR loop would expand together with the low-lying Ca loop if they were of the same emerging flux system. Another possibility is that the SXR loop brightening represents heating during magnetic reconnection in a curved current sheet between the emerging and ambient fields, as suggested by Yoshimura & Kurokawa (1999) who found SXR brightening above emerging Hα arch filaments. However, the location of the event within the inferred coronal hole poses a challenge for the existence of such a hot SXR loop as observed here. The nature of this transient SXR loop brightening thus remains an open question.

5. CONCLUSIONS

We have presented multiwavelength observations and detailed analysis of a chromospheric jet and its accompanying growing loop. This extends the study presented in Paper I which focused on the fine structure and kinematics of the jet itself. We summarize our new observations as follows.

1. Potential field extrapolation indicates that this event occurs in an equatorial coronal hole and as expected, the jet is closely aligned with the open-field lines (Figures 5 and 6).
2. The predecessor of the jet is a bundle of material threads ($\lesssim 1^{"}$ wide) extending from the chromosphere into the corona. This bundle exhibits transverse sinusoidal oscillations across its axis, whose velocities range from 47 ± 9 to 58 ± 11 km s$^{-1}$, periods from 162 ± 11 to 197 ± 35 s, and amplitudes from 1.5 ± 0.3 to 1.7 ± 0.3 Mm. Such oscillations propagate upward at velocities as high as $v_{ph} = 786 \pm 30$ km s$^{-1}$ (Figures 8 and 9). We interpret these as evidence of propagating torsional MHD waves.
3. The material bundle first slowly and then rapidly swings up, with the orientation angle of its central axis from the limb growing by $>50^{"}$ in 10 minutes (Figure 10). The transition from the slow-to-fast swing phase coincides with the onset of an A4.9 flare, which heats the plasma to $T = 12.2 \pm 0.6$ MK. The bundle then swings back in a whip-like manner and develops into a collimated jet (Figure 3), which continues to exhibit transverse oscillations (see Paper I), but at fractionally slower rates than the earlier bundle mentioned above.
4. A loop expands simultaneously in these two phases. It attains a uniform vertical velocity of $16.2 \pm 0.4$ km s$^{-1}$ during the gradual phase and reaches $135 \pm 4$ km s$^{-1}$ at the end of the acceleration phase (Figure 10). The initial slow rise velocity is similar to those of emerging fluxes found in Hα arch filaments and in MHD simulations. The lateral expansion is asymmetric and dominated by the northward displacement of the northern leg.
5. The loop appears to rupture or collapse near the peak of the flare and its apex becomes undetectable first. The northern leg of the loop retreats downward and material drains down to the photosphere at accelerations ($a = (-4.8 \pm 0.7) g_\odot$) greater than free-fall. At the same time, some material is ejected upward ($a = (11.4 \pm 3.1) g_\odot$) in the same leg (Figures 11 and 12; Section 4.2).
6. Some material falls back along streamlines in the original direction of ascent, showing no more transverse oscillations (Paper I). Most of the streamlines swerve around an inferred dome extending above the chromosphere and characterized with a null point at its top, depicting an inverted-Y geometry. These streamlines closely match in space the late Ca loop prior to its rupture, the X-ray flare loop, and the EUV absorption features (Figure 13).

We interpret (Section 4) these observations in the framework of the emergence of a twisted flux rope into an open-field environment leading to the formation of a jet through magnetic reconnection (e.g., Heyvaerts et al. 1977; Yokoyama & Shibata 1995; Moreno-Insertis et al. 2008), and the relaxation of twists transferred into the jet leading to its spin (Shibata & Uchida 1985, 1986; Canfield et al. 1996; Török et al. 2009). We further identify signatures of the fan–spine topology throughout the event, from the precursor to post-eruption evolution. The outer spine is recognized as the material bundle that eventually develops into the collimated jet, while the fan surface is imaged as the growing Ca loop in projection. After the eruption, the presence of this magnetic skeleton is clearly implied by the streamline geometry of the falling material.
Our observations and model share commonalities with their counterparts in the literature, while the major differences given by our new findings are as follows.

1. The simultaneous growth of the emerging flux and development of the resulting jet, synchronized in two stages (Figure 10), have been clearly established here for the first time, to the best of our knowledge. Growing loops (other than post-flare loops) were recently noted in X-ray jet events (Shimojo et al. 2007; Chifor et al. 2008), but their detailed temporal evolution and relationship with the jet were not clear.

2. In previous models (e.g., Yokoyama & Shibata 1995), reconnection between the emerging flux and the overlying field would immediately lead to the launch of an eruptive jet. In our case, when the reconnection rate is moderate early in the event, the jet, manifesting itself as the material bundle, undergoes quasi-static evolution for more than 20 minutes. We call this an “intermediate jet” stage, which later develops into the classical eruptive jet as a result of fast reconnection driven by the accelerating expansion of the emerging flux. These are analogous to the slow and fast reconnections in the energy-storage and energy-release stages of coronal jet simulations, respectively (Pariat et al. 2010).

3. The whip-like motion of a jet has been predicted as a consequence of the sling-shot effect of the newly reconnected field lines (e.g., Shibata & Uchida 1985; Canfield et al. 1996) and has been observed as a unidirectional swing away from the accompanying flare where reconnection occurs. In our case, the axis of the material bundle swings back and forth, and the previously predicted whip motion only applies to the second swing here when the material bundle moves into its collimated jet position. We interpret this as instabilities possibly related to the catastrophic unload of excessive twists (Section 4.1).

A statistical study of similar Hinode events is required before more general conclusions can be drawn. The validity of our phenomenological interpretation shall also be rigorously checked against theoretical models, numerical simulations (e.g., Pariat et al. 2010), and laboratory experiments (e.g., Bellan et al. 2005). Finally, as pointed out by Antiochos (1998), the emergence of a bipolar flux system in a unipolar region on the photosphere naturally produces a local minority-polarity region with a spine–fan helmet magnetic structure above it. Our observations clearly show such an event and have identified its observable dynamical characteristics, thus providing motivation for future investigation of the rich three-dimensional magnetic topologies to be found in such structures.

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APPENDIX A

IMAGE PROCESSING AND CROSS-INSTRUMENT COALIGNMENT

We describe below the procedures to process and coalign images obtained from RHESSI, TRACE, Hinode XRT and SOT, YNAO, and STEREO EUVI. The absolute solar coordinates of RHESSI images have subarcsecond accuracy owing to its limb sensing aspect system and star-based roll angle measurements (Fivian et al. 2002). We thus used RHESSI images as a fiducial for our coalignment.

XRT images were processed using the xrt_prep and xrt_jitter routines. We selected three XRT images (at 02:50:49, 02:51:51, and 02:53:51 UT, exposure <1 s) during the flare in which over-exposure was minimal. We then constructed three RHESSI images at 3–6 keV with 100 s integration centered at these times. Assuming these XRT and RHESSI emissions were from the same source at each time, we shifted the XRT image to match its centroid of the 99% brightness contour and that of the 50% contour of the corresponding RHESSI image. The averages of the required shifts at the three times are $\Delta x = 10.3'$ and $\Delta y = 11.3'$ in the solar west and north directions, respectively. By rotating the shifted XRT images about the RHESSI centroid to match the limb in a trial-and-error manner, we found that no additional rotation is needed and the $y$-axis is already the solar north.

To coalign TRACE 195 Å images, we noted that both TRACE and XRT observed flare loops except that XRT loops are hotter and located at slightly higher altitudes. Thus we selected a pointing-corrected XRT image at 02:53:51 UT and a later TRACE image at 02:59:14 UT (when the hot XRT loops had cooled down) to match their flare loop legs. The TRACE image was required to be shifted by $\Delta x = -3''$ and $\Delta y = 14'$, and then rotated by 1˚ counterclockwise about the centroid of the flare loop, $O = [975', -42']$, to match the limb.

For SOT observations, we first processed Ca ii H images using the standard fg_prep routine with the /no_pointing option to disable automatic pointing correction which is currently not satisfactory. We then made relative coalignment by cross-correlating neighboring images. To find the absolute image coordinates, we noted that the $\leq 2 \times 10^6 K$ Ca ii H emitting plasma appeared as absorption in TRACE 195 Å images. We then selected a pointing-corrected TRACE image at 02:43:20 UT with a 65 s integration and summed the corresponding SOT images from 02:43:23 to 02:44:19 UT. By matching features including the jet material bundle, large spicules, and the limb, we found that the center of the SOT image must be placed at $x = 998'9$ and $y = -32'3$, and then the image should be rotated by 0.2 clockwise about point $O = [975', -42']$.

YNAO Hz images were shifted and rotated to match the jet features in neighboring SOT images. STEREO EUVI images were processed using the mk_sech3_map routine that takes into account the pointing information of the spacecraft, with the /rotate_on option turned on to make the solar north the y-axis. We did not attempt to align images from EUVI and other instruments, since STEREO has a different distance and view angle to the Sun compared with the Earth view. Meanwhile, the two STEREO spacecraft were too close to allow for triangulation in three-dimensional geometry at the time of the event.

The translation and rotation corrections found above were applied to all images from the corresponding instruments. The overall accuracy are 1''–2'' and 2''–3'' in the x- and y-directions, respectively.
Figure 15. (a) Spatially integrated RHESSI X-ray spectrum at the peak of the flare, averaged among detectors 1, 4, and 6 and fitted with an isothermal model. (b) Fitting residuals normalized to the 1σ uncertainty of the measured flux at each energy.

(A color version of this figure is available in the online journal.)

APPENDIX B

RHESSI SPECTRAL ANALYSIS

To determine the temperature of the flare plasma, we fitted RHESSI X-ray spectra. Following Krucker et al. (2007), we used detectors 1, 4, and 6, which had suffered the least radiation damage by the time of the event (five years after the launch) and had the best spectral resolution among the nine germanium detectors. We fitted the spectral data from each individual detector separately, averaged the fitting parameters among the three detectors to give the final result, and used their standard deviations as the uncertainties. Details of this procedure were described in Liu et al. (2008) and Milligan & Dennis (2009). Figure 15 shows the spectrum at the peak of the flare, which is best fitted with an isothermal model and yields a temperature of $T = 12.2 \pm 0.6$ MK and emission measure of $EM = (5.3 \pm 0.5) \times 10^{45}$ cm$^{-3}$. There is pronounced ion line emission at 6.7 keV and no signature of nonthermal emission.

APPENDIX C

NATURE OF Ca ii H EMISSION DISPLACEMENTS

The resonance H line emission of Ca$^{+}$ ions has contributions from scattering of photospheric radiation and from thermal emission (collisional excitation). In general, the former decreases with temperature because of progressive ionization and the latter increases with temperature because of increased collisional rates. The emission decreases sharply with temperature when $T \gtrsim 2 \times 10^4$ K (Gouttebroze et al. 1997).

Based on the following reasonings, we believe that the displacements of Ca emission features presented in this paper primarily result from mass motions rather than sequential excitations of emission due to temperature or density variations. The Ca$^+$ H line emitting plasma has typical temperatures of $\lesssim 2 \times 10^4$ K, which is in the temperature range of the chromosphere. The Ca material bundle and loop also first appear at spicule heights in the chromosphere and then develop upward. This suggests a chromospheric origin of the material that is likely of high density as a result of flux emergence discussed in Section 4. In addition, such features are no weaker in Ca$^{+}$ H emission and in 195 Å absorption than the nearby prominence (Figure 4) at similar temperatures. This prominence, clearly visible in AR 10940 through its entire disk passage (http://www.solarmonitor.org/index.php?date=20070206), is now just behind the limb and in the background of the event. Assuming that they have comparable line-of-sight extents, the density of the prominence, which has typical values of $10^{11}$ to $10^{12}$ cm$^{-3}$, provides a lower limit for the density in the Ca material bundle, loop, and jet. This inference has two implications: (1) the temperature of the dense, cool material distributed in such an extended volume (cf. the compact flare site) is not expected to change rapidly because of its large heat capacity, and thus the motions of these Ca emission features are unlikely a result of sequential temperature variations on such short timescales of $\sim 10$ s; and (2) more importantly, these features are two orders of magnitude denser than the ambient corona, and thus their motions are unlikely a consequence of sequential compression of coronal plasma either. Moreover, compression would heat the million degree coronal plasma to even higher temperatures that are further away from the Ca$^{+}$ H emission regime of two orders of magnitude cooler. For comparison, in an MHD experiment (Pariat et al. 2009), the compressional density enhancement responsible for supplying mass to a jet from a coronal origin is merely a factor of two.

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