MAGNETIC FLUX CANCELLATION AS THE TRIGGER OF SOLAR QUIET-REGION CORONAL JETS

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ABSTRACT

We report observations of 10 random on-disk solar quiet-region coronal jets found in high-resolution extreme ultraviolet (EUV) images from the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly and having good coverage in magnetograms from the SDO/Helioseismic and Magnetic Imager (HMI). Recent studies show that coronal jets are driven by the eruption of a small-scale filament (called a minifilament). However, the trigger of these eruptions is still unknown. In the present study, we address the question: what leads to the jet-driving minifilament eruptions? The EUV observations show that there is a cool-transition-region-plasma minifilament present prior to each jet event and the minifilament eruption drives the jet. By examining pre-jet evolutionary changes in the line of sight photospheric magnetic field, we observe that each pre-jet minifilament resides over the neutral line between majority-polarity and minority-polarity patches of magnetic flux. In each of the 10 cases, the opposite-polarity patches approach and merge with each other (flux reduction between 21% and 57%). After several hours, continuous flux cancelation at the neutral line apparently destabilizes the field holding the cool-plasma minifilament to erupt and undergo internal reconnection, and external reconnection with the surrounding coronal field. The external reconnection opens the minifilament field allowing the minifilament material to escape outward, forming part of the jet spire. Thus, we found that each of the 10 jets resulted from eruption of a minifilament following flux cancelation at the neutral line under the minifilament. These observations establish that magnetic flux cancelation is usually the trigger of quiet-region coronal jet eruptions.

Key words: Sun: activity – Sun: filaments, prominences – Sun: photosphere

Supporting material: animations

1. INTRODUCTION

Solar coronal jets are frequent magnetically channeled narrow eruptions observed in the solar corona (Raouafi et al. 2016). They are relatively short lived and transient features, occurring in various solar environments including quiet regions (Wang et al. 1998a; Hong et al. 2011), coronal holes (Shimojo et al. 1998; Cirtain et al. 2007; Adams et al. 2014) and active regions (Shibata et al. 1992; Innes et al. 2011; Panesar et al. 2016; Sterling et al. 2016). They have been often observed in extreme ultraviolet (EUV; Wang et al. 1998b) and X-ray (Shibata et al. 1992; Canfield et al. 1996; Alexander & Fletcher 1999) emission. X-ray jets are well-studied and imaged by Yohkoh and Hinode. Most X-ray jets have a lifetime of about 10 minutes, velocities of around 200 km s⁻¹, and lengths of ~5 × 10⁴ km s⁻¹ (Shimojo et al. 1996; Savcheva et al. 2007). It has been observed that X-ray jets show a bright point (also known as jet bright point, JBP) at an edge of the base during the eruption (Shibata et al. 1992). Properties (e.g., velocities, lifetimes, and a JBP) similar to X-ray jet properties have been seen in EUV coronal jets (Raouafi et al. 2008; Nisticò et al. 2009; Pucci et al. 2013; Schmieder et al. 2013).

A possible driving mechanism for jet eruptions is explosive magnetic reconnection. However, the triggering and driving mechanisms are still not fully understood. Some workers have suggested that flux emergence may lead to the jet eruption (e.g., Shibata et al. 1992, 2007; Moreno-Insertis et al. 2008). A few on-disk studies showed evidence of flux cancelation leading to the jet eruption (Hong et al. 2011; Huang et al. 2012; Shen et al. 2012; Adams et al. 2014; Young & Muglach 2014a, 2014b), but until now there have been no systematic observational studies of the magnetic origin of jet eruptions. Sterling et al. (2015) analyzed 20 random coronal jets in polar coronal holes using soft X-ray and EUV images and found that those X-ray jets are driven by small-scale filament eruptions. Their study included only near-limb events that therefore lacked adequate magnetic field data, and so the question of what leads to these minifilament eruptions remained open.

In this Letter, we investigate the eruption mechanism of 10 random jets in on-disk quiet regions. We study the photospheric magnetic field evolution leading to the jet eruptions. That is, we track the evolution of the photospheric magnetic flux that leads to the minifilament eruption in jets. A key question we address in this Letter is, what causes the jet eruptions: magnetic flux cancelation or flux emergence? By studying 10 random jets, we find that flux cancelation is the cause of most quiet-region jet eruptions.

2. INSTRUMENTATION AND DATA

Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) gives full-Sun images with high spatial resolution (0.76 pixel⁻¹, ~430 km) and high temporal cadence (12 s) in seven EUV wavelength bands (Lemen et al. 2012). For the present study, we used multi-channel (304 Å, 171 Å, and 94 Å) EUV images from SDO/AIA to view cool-transition-region structures (minifilaments) and coronal-temperature jet structures (e.g., JBP). We primarily used 171 Å images because we found pre-jet minifilaments to be best seen in this channel.
Table 1
Measured Parameters for the Observed Quiet-region Jets

| Event No. | Date     | Time* (UT) | Location\(^b\) | Jet Speed\(^d\) (km s\(^{-1}\)) | Jet Dur.\(^d\) min. | Jet-Base\(^e\) Width (km) | Minifil. Length\(^f\) (±1700 km) | Φ Values\(^g\) 10\(^{19}\) Mx | % of φ\(^b\) |
|-----------|----------|------------|----------------|-------------------------------|---------------------|--------------------------|----------------------------------|----------------|------|
| J1        | 2012 Mar 22 | 04:46      | −470, −100     | 100 ± 30                      | 15 ± 5              | 10500 ± 500              | 9800                             | 1.6            | 52 ± 5.8 |
| J2        | 2012 Jul 04  | 08:32      | −44, 285       | 100 ± 10                      | 10 ± 2              | 27000 ± 500              | 25000                             | 4.0            | 18 ± 6.8 |
| J3        | 2012 Jul 07  | 21:31      | −192, −180     | 120 ± 15                      | 14 ± 3              | 16500 ± 400              | 10500                             | ...            | ...     |
| J4        | 2012 Aug 05  | 02:20      | −485, 190      | 140 ± 35                      | 10 ± 3              | 22000 ± 1000             | 31000                             | 1.5            | 21 ± 6.0 |
| J5        | 2012 Aug 10  | 23:03      | −168, −443     | 125 ± 15                      | 15 ± 2              | 16000 ± 400              | 10000                             | 0.9            | 57 ± 5.4 |
| J6        | 2012 Sep 20  | 22:56      | −158, −486     | 35 ± 5                        | 9 ± 2               | 20000 ± 500              | 36000                             | 2.0            | 23 ± 4.6 |
| J7        | 2012 Sep 21  | 03:33      | −115, −485     | 135 ± 30                      | 12 ± 1              | 17500 ± 500              | 15000                             | 1.0            | 36 ± 7.2 |
| J8        | 2012 Sep 22  | 01:25      | −338, 103      | 110 ± 45                      | 11 ± 1              | 13000 ± 600              | 5700                              | 0.9            | 50 ± 5.1 |
| J9        | 2012 Nov 13  | 04:21      | −28, −307      | 55 ± 5                        | 9 ± 3               | 18000 ± 1000             | 25000                             | 1.7            | 34 ± 3.2 |
| J10       | 2012 Dec 13  | 10:36      | 26, 50         | 65 ± 20                       | 10 ± 2              | 9500 ± 500               | 12500                             | 1.2            | 38 ± 5.0 |

Notes.

* Time of JBP approximate peak brightening in AIA 94 Å images.
\(^b\) Approximate location of the jet region on the solar disk.
\(^d\) Plane-of-sky speed along the jet spire (observed in AIA 171 Å emission images), soon after jet started to erupt outward. Speeds and uncertainties are estimated from the time–distance plots.
\(^e\) Duration of jet spire visibility in 171 Å.
\(^f\) Mean cross-sectional width of the jet-base region measured at the time of peak base brightening.
\(^g\) Integrated length (along the curvilinear path) of the minifilament before eruption onset.
\(^h\) Average flux (Φ) values of the minority flux clumps 5–6 hr before eruption.
\(^i\) Flux change between 5–6 hr before eruption and 0–1 hr after eruption.
\(^j\) Flux patches are not isolated enough for a reliable measurement.
\(^k\) There are two eruptions in the jet region, the first at 02:00 and the second at 02:20; J4 is the second eruption.

We use line of sight magnetograms from the SDO/ Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) with high spatial resolution of 0.5 pixel\(^{-1}\) and temporal cadence of 45 s (Scherrer et al. 2012) to examine the photospheric magnetic field of the jet region. With these magnetograms we follow the pre-jet evolution of the photospheric magnetic field of the jet-base region, while examining nearly concurrent EUV images of coronal emission.

We downloaded SDO/AIA and SDO/HMI data from the JSOC cutout service* and removed solar rotation by derotating all of the AIA and HMI images to a particular time. AIA and HMI data sets were co-aligned by using SolarSoft routines, and we overplotted the HMI contours of active-region magnetic fields on to the AIA images to verify the alignment. We created movies at two lower temporal cadences (1 and 5 minutes for AIA and HMI, respectively) to study the jet dynamics and the jet-region magnetic evolution.

3. RESULTS

3.1. Overview

We examine the structure and evolution of 10 EUV on-disk quiet-region jets (between 2012 March and December), relating the jet-base field structure observed by SDO/HMI to jet coronal components observed by SDO/AIA. Table 1 lists the 10 jets and their measured parameters. In Section 3.2, we present the EUV observations of 2 jets from our list of 10 jets. The pre-jet magnetic evolution is addressed in Section 3.3.

3.2. Evolution of Minifilaments and Jets

Figure 1 shows a typical example of one of our EUV on-disk jets (J7; Table 1). We observed a minifilament in the jet-base region (Figures 1(a) and (d)). It had a length of about 15,000 km (Table 1). Figure 1(a) shows the situation prior to the jet onset. Later, the minifilament takes part in the eruption. The animation accompanying Figures 1(a)–(c) shows the evolution of the minifilament and jet. The minifilament starts to lift off at ~03:25 UT and the JBP appears at 03:29 UT (see the animation and Figures 1(b), (c), (e), and (f)). The JBP occurs at the pre-eruption location of the minifilament. After the start of the JBP, the jet spire starts to extend upward, as shown in Figures 1(c) and (f).

In Figure 2, we show another example jet (J9) from our list. The white arrow in Figure 2(a) points to a minifilament in the jet-base region. The minifilament has a length of ~25,000 km (Table 1). Figure 2(b) shows the minifilament as it was rising slowly. The JBP starts to brighten at 04:23 UT (animation of Figure 2) and later the spire becomes visible (Figure 2(c)). Figures 2(c) and (f) show that the JBP sits at the pre-eruption location of the minifilament. We do not observe any precursor brightenings at the location of the JBP in AIA 1600 and 1700 Å images. In all 10 events, the JBP brightening appears at the same time in the AIA EUV images and in the AIA 1600 Å images.

Similarly, the other eight jets resulted from eruption of minifilaments. Specifically, each of the jets resulted from the eruption of a minifilament from the site of the JBP. All the jet-producing eruptions and JBP studied here are similar to typical solar flare eruptions (e.g., McCauley et al. 2015), in which a flare arcade (analogous to the JBP) grows over the neutral line in the wake of the filament eruption. The minifilaments show a slow rise, followed by a fast rise as they erupt (animation a of Figure 1 and animation a of Figure 2), analogous to many longer-scale filament eruptions (e.g., Sterling & Moore 2005; Panesar et al. 2015).

We measured the length of the minifilaments, the jet-base widths, the jet speeds, and jet durations (between the start and
the maximum extent of the spire) from the AIA 171 Å images. All of the measured parameters are given in Table 1. We measured the plane-of-sky speeds of the jets by constructing a height-time plot for each of them. For the uncertainties, we considered different fits to the height-time trajectories, and estimated the error in the speeds from the measured slopes. So for our two events above, we observed that J7 moves with a speed of $135 \pm 30$ km s$^{-1}$ over about 12 minutes, whereas J9 erupts outward with a speed of $55 \pm 5$ km s$^{-1}$ over about 9 minutes.

### 3.3. Underlying Magnetic Field

Figures 1(g)–(i) show line of sight magnetograms before, during, and after the eruption onset of jet J7. Figure 1(d) shows...
that the mini-filament initially resides along a neutral line in the quiet-region magnetic network. This is a region where positive flux is in the majority and the mini-filament runs along the neutral line between majority and minority flux clumps (shown with yellow arrows in Figure 1(g)). We followed these positive and negative flux clumps before eruption and observed that they converged (see Figures 1(g)–(i) and animation b). The yellow arrows in Figure 1(g) point to positive and negative clumps that converge, merge, and mostly cancel leading up to the mini-filament eruption.

To examine the evolution of the magnetic flux quantitatively we measured the negative flux of the jet region (J9), bounded by the white box of Figure 1(h). We measured only the negative flux because it is easy to isolate the patch of negative...
polarity. We carefully checked that there were no negative flux flows across the boundary of the box. Figure 3(a) shows the negative flux values, integrated over the selected region (white box of Figure 1(h)), as a function of time. The negative flux continuously decreases with time, which is clear evidence of flux cancelation at the neutral line of the minifilament. The dashed line in Figure 3(a) marks the eruption time, i.e., when we observe brightening in the EUV images (see animation a of Figure 1) and the minifilament starts to lift off. To further display the flux convergence and cancelation, we created an HMI time–distance image (~18 hr, Figure 3(b)) along the red dashed line of Figure 1(h). One can clearly see that both polarities approach the neutral line, and eventually cancel with each other just before the eruption (at 03:27 UT, red line in Figure 3(b)). The cancelation of the two clumps continues on even after the jet eruption (animation b of Figure 1).

Figures 2(g)–(i) shows the magnetic flux arrangement for jet J9. The minifilament initially resides along the neutral line that runs between a clump of majority black flux and a clump of minority white flux at one end. Both clumps (shown with the yellow arrows in Figure 2(g)) merged and mostly canceled with each other (see animation b of Figure 2). For this jet we mainly focus on the changes in the positive (white) flux, which is the minority flux for this case, because it is more isolated: its evolution is easy to follow and measure. The plot in Figure 3(c) shows the evolution of the positive flux for ~6 hr. The flux continuously decreased through the time (~04:23 UT) of the appearance of the JBP at the pre-eruption site of the minifilament. This is clear evidence of flux cancelation at the location of minifilament leading to the eruption. The minifilament starts to lift off before the jet-spire onset. The time–distance image in Figure 3(d) shows the convergence and cancelation of the jet-base polarities (Figure 1(h)) for ~12 hr. As the negative flux cancels and disappears, the jet eruption is triggered at 03:50 UT.

Similarly, we tracked the evolution of magnetic flux in all eight other jet regions and compared that evolution with the minifilament eruption onset time and find flux cancelation in each case. We estimated the percentage flux reduction from well before to after each of the 10 events by calculating the flux...
content of the minority-polarity flux clumps 5–6 hr before and immediately (0–1 hr) after the jet eruption (Table 1). We estimated the (1σ) uncertainty in flux decrease using images of the 5 minute cadence flux values over the 1 hr windows (5–6 hr before and 0–1 hr after the eruption). These uncertainties are listed in Table 1.

We find that the triggering mechanism for all 10 jet eruptions is evidently flux cancelation in the manner of our 2 example jets. This is consistent with the idea of other workers, e.g., Hermans & Martin (1986), Jiang & Wang (2001), Sakajiri et al. (2004), and Ren et al. (2008), that flux convergence and cancelation plays an important role in small-scale filament eruptions. In those listed studies, the small-scale filaments are smaller than typical solar filaments but larger than our mini-filaments.

4. SUMMARY AND DISCUSSION

We have examined in detail 10 randomly found on-disk quiet-region jets observed by SDO/AIA and SDO/HMI. They appear to be typical coronal jets and have these properties: (a) in each pre-jet jet base there was cool transition region material, a mini-filament, consistent with recent findings of Sterling et al. (2015); (b) the jets shoot out from the solar surface with an average speed of 100 ± 20 km s⁻¹; (c) the average duration of the studied jets is 12 minutes; (d) the average jet-base width is 17,000 ± 600 km; (e) the average length of the mini-filament is 18 × 10³ km, which is comparable to the jet-base width. In all cases, we observed a JBP at the neutral line from which the mini-filament erupted. The jet-spire widths grew to about the width of the jet base; this is similar to what Moore et al. (2010) found for their blowout jets, based on X-ray observations.

The observed jet speeds and durations are somewhat slower and shorter than those obtained for quiet-region X-ray jets by Shimojo et al. (1996) (~125 km s⁻¹, 65 minutes). Our jet durations are nearly the same as the average lifetime (~20 minutes) of EUV jets reported by Nisticò et al. (2009), and similar to that of the X-ray coronal hole jets of Savcheva et al. (2007) (~10 minutes). Our mini-filament lengths are ~2 times longer than those of Sterling et al. (2015) (~8 × 10³ km); we measured the total curvilinear length along the mini-filament body for our quiet-region mini-filaments before eruption, while they measured the projected length of polar coronal hole mini-filaments during eruption.

The mini-filament eruptions are similar to many large filament eruptions, in showing slow rise followed by fast rise. The mini-filaments initially lie on the magnetic neutral lines between the majority and minority flux and they erupt during flux cancelation at the neutral line. Magnetic flux cancelation is evidently the triggering mechanism in the studied jet eruptions (and evidently works in the way proposed by Moore & Roumeliotis 1992 for larger filament eruptions).

Figure 4 shows a schematic sketch based on our jet observations. In Figure 4(a), a smaller (explosive) bipole (on right-hand side) is next to a larger bipole (left-hand side), where the smaller bipole contains a sheared and twisted field that holds a mini-filament. The mini-filament (blue) initially sits between the patches of majority positive flux and minority negative flux. The field immediately above (black loops in panel (a)) is an overlying pre-eruption arcade. Initially, the smaller bipole’s footpoints are well separated from each other. In panels (b) and (c), we show that both polarities are approaching (and canceling) each other (see Figures 3(b), (d)). The resulting highly sheared filament field eventually becomes unstable due to flux cancelation at the neutral line and erupts outward, resulting in internal reconnection in the erupting field (lower star in panels (b) and (c)). The JBP is the lower product of the internal reconnection and is shown as low-lying (red) flare loop in panel (b) at the pre-eruption location of the mini-filament. As it erupts, the outer envelope of the erupting mini-filament field reconnects (known as external/interchange reconnection) with the surrounding far-reaching coronal field above the large bipole (upper star in panels (b) and (c); from AIA images we know that the surrounding coronal field is often a far-reaching loop rather than truly open). The external reconnection results in two new connections: the red closed loop in panel (c) over the large bipole and the red open field line, which guides along it the mini-filament plasma that appears as part of the jet spire. We observe brightenings in EUV images (Figures 1(e) and 2(e)) from the external reconnection at the far ends of the red closed loops that are newly formed from the reconnection (see Figures 1(b), 2(b), and 4(c)).
In summary, we report observations of 10 random on-disk solar quiet-region jets. We address the magnetic cause of the driving eruptions. Our observations show that in each case a mini-filament initially resides at a neutral line inside the jet-base region, and flux cancelation at that neutral line triggers the jet-driving mini-filament eruption.

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