Magnetic Flux Cancelation as the Trigger of Solar Coronal Jets in Coronal Holes

Navdeep K. Panesar1, Alphonse C. Sterling1, and Ronald L. Moore1,2
1 NASA Marshall Space Flight Center, Huntsville, AL 35812, USA; navdeep.k.panesar@nasa.gov
2 Center for Space Plasma and Aeronomic Research (CSPAR), UAH, Huntsville, AL 35805, USA

Abstract

We investigate in detail the magnetic cause of minifilament eruptions that drive coronal-hole jets. We study 13 random on-disk coronal-hole jet eruptions, using high-resolution X-ray images from the Hinode/X-ray telescope (XRT), EUV images from the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA), and magnetograms from the SDO/Helioseismic and Magnetic Imager (HMI). For all 13 events, we track the evolution of the jet-base region and find that a minifilament of cool (transition-region-temperature) plasma is present prior to each jet eruption. HMI magnetograms show that the minifilaments reside along a magnetic neutral line between majority-polarity and minority-polarity magnetic flux patches. These patches converge and cancel with each other, with an average cancelation rate of ∼0.6 × 1018 Mx hr⁻¹ for all 13 jets. Persistent flux cancelation at the neutral line eventually destabilizes the minifilament field, which erupts outward and produces the jet spire. Thus, we find that all 13 coronal-hole-jet-driving minifilament eruptions are triggered by flux cancelation at the neutral line. These results are in agreement with our recent findings for quiet-region jets, where flux cancelation at the underlying neutral line triggers the minifilament eruption that drives each jet. Thus, from that study of quiet-Sun jets and this study of coronal-hole jets, we conclude that flux cancelation is the main candidate for triggering quiet-region and coronal-hole jets.

Key words: Sun: activity – Sun: filaments, prominences – Sun: flares – Sun: magnetic fields

Supporting material: tar.gz files

1. Introduction

Solar coronal jets are dynamic, evanescent, and beam-like structures that often appear bright in coronal images (Raouafi et al. 2016). Regardless of the solar cycle, jets are pervasive solar phenomena, with some reaching heights of several hundred km in EUV and X-ray images (Shimojo et al. 1996; Savcheva et al. 2007; Shibata et al. 2007). White light jets, at least some of which are correlated with coronal jets, can reach several R☉ (e.g., Wang et al. 1998; Ko et al. 2005). They occur in all types of solar environments: active regions (Shibata et al. 1992; Panesar et al. 2016a; Sterling et al. 2016), quiet regions (Innes et al. 2016; Panesar et al. 2016b), and coronal holes (Nistico et al. 2009; Sterling et al. 2015). Jets are more prominent and often seen best in coronal-hole regions because the jet plasma is observed in emission against a dark coronal background in EUV and X-ray images (Cirtain et al. 2007; Sterling et al. 2015).

Recent observations by Sterling et al. (2015) showed that polar coronal-hole jets are driven by minifilament eruptions, and a jet bright point (JBP) appears at the location from where the minifilament erupted. Later, Panesar et al. (2016b) studied 10 on-disk quiet-region jets and found that the same minifilament eruption idea also holds for coronal jet generation in quiet regions. They also investigated the triggering mechanism of their quiet-Sun coronal jets, and found strong evidence that progressive magnetic flux cancelation at a neutral line under the minifilament between majority-flux and minority-flux clumps eventually destabilizes the field holding the minifilament material, resulting in an outward eruption of the minifilament. In each of the 10 events, Panesar et al. (2016b) found clear evidence of ongoing flux cancelation at the neutral line.

Very recently, Panesar et al. (2017) investigated the formation mechanism of quiet-region pre-jet minifilaments that erupted to generate the jets that they analyzed in Panesar et al. (2016b). In Panesar et al. (2017), they mainly investigated the longer-term magnetic field evolution that led to the formation of the pre-jet minifilaments. They found that opposite-polarity flux patches converged and partially canceled, before and during the formation of the minifilaments over the neutral line between the converging flux patches. Continuous flux cancelation over several hours resulted in thickening and increased prominence of the minifilaments at the neutral line. Eventually, flux cancelation between the opposite-polarity flux patches triggered each minifilament eruption, leading to the jet. In summary, from our previous study of quiet-region jets (Panesar et al. 2016b, 2017), we infer that in quiet regions, magnetic flux cancelation is the main process for the buildup of the sheared and twisted field of the pre-jet minifilament, and is also the trigger of the minifilament’s eruption that makes the jet. In addition, Sterling et al. (2016, 2017) found that, at least in most of the cases they examined, active-region jets resulted from flux cancelation.

Because Sterling et al. (2015) studied polar coronal-hole jets, their events were too close to the solar limb for reliable magnetic field investigations. Thus, from the study of polar coronal-hole jets by Sterling et al. (2015), the question of whether coronal-hole jets follow the flux cancelation idea (that flux cancelation triggers the minifilament jet eruptions) remained open. In Panesar et al. (2016b), we found in on-disk quiet regions that coronal jets originate at a neutral line between dominant-polarity flux and a patch of canceling minority-polarity flux. Because we expect to have this same arrangement of canceling dominant-polarity and minority-polarity flux at each jet base in coronal holes, we expect that on-disk coronal-hole jets work in the same fashion as on-disk...
quiet-region coronal jets. To test this hypothesis, here we investigate the on-disk coronal jet eruptions.

In this study, we study the triggering mechanism of 13 randomly selected on-disk coronal-hole jets, using images from the Hinode/X-ray telescope (XRT) and from the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA), and using photospheric magnetograms from the SDO/Helioseismic and Magnetic Imager (HMI). We systematically track the photospheric magnetic field evolution that leads to coronal-hole jets. We find that flux cancelation is the main process that triggers the coronal-hole jet eruptions, as in quiet-region jets.

2. Instrumentation and Data

SDO/AIA provides full Sun images with high spatial resolution (0.6′′/pixel, ~430 km) and temporal cadence (12 s) in seven EUV wavelength bands (Lemen et al. 2012). For our investigations we use SDO/AIA EUV images (304, 171, 193, 211, and 94 Å) to view the transition-region-temperature and coronal-temperature jet plasma structures.

To study the longer-term photospheric magnetic field evolution of the jet-base region, we use line-of-sight magnetograms from the SDO/HMI; Schou et al. 2012), with a high spatial resolution of 0.5′′/pixel and temporal cadence of 45 s (Scherrer et al. 2012).

We also use Hinode/XRT (Golub et al. 2007) data, when available, to view the coronal-temperature jet structures. Our XRT images have a limited field of view and a spatial resolution of 1.0′′/pixel, and with differing temporal cadences. XRT is sensitive to hot coronal emissions, detecting features of temperature $\gtrsim 1.0 \times 10^6$ K.

3. Triggering of Minifilaments and Jets

3.1. Jet (J11)

Figures 1(a)–(c) show 171 Å AIA images of the jet region with and without HMI contours. Figures 1(d)–(f) display the HMI photospheric magnetic field of the jet region. The accompanying movies (MOVIE1a and MOVIE1b) show the complete evolution of the pre-jet region. We first examine this pre-jet region in detail using AIA and XRT images. From the AIA images, we see that the minifilament was present at the neutral line at least $\sim 1$ hr before the eruption onset. This coronal hole has a dominant negative polarity, and prior to eruption (Figure 1), the minifilament resides on the neutral line (yellow line in 1(e)) between majority-polarity (negative) and minority-polarity (positive) flux clumps (Figures 1(a) and (d)). From about 14:59 UT, the minifilament starts moving outward from the solar surface and then a JBP (white arrow in Figure 1(b)) appears underneath the rising minifilament. At the same time, a JBP appears in the XRT and 94 Å AIA images.
After 15:04 UT, the mini-filament is completely ejected and becomes a part of the jet spire (Figure 1(c) and MOVIE1a). The mini-filament moves outward with an average speed of 105 ± 30 km s⁻¹. During the rise of the mini-filament, external brightenings start to appear at the far side of the majority-polarity (negative) flux clump. The AIA hotter channels (e.g., 94 Å) and XRT images also show the signature of external brightenings at the majority-polarity negative flux clump (Figures 1(b) and 2). This situation is broadly consistent with the polar coronal jet observations and schematic picture of Sterling et al. (2015). The magnetic evolution of this jet is shown in Figure 3, and will be discussed in Section 4.

3.2. Jet J1

In Figure 4, we show our second detailed example of a jet, J1 from Table 1. The high-cadence AIA movie (MOVIE2a) accompanying Figures 4(a)–(c) shows the evolution of the mini-filament eruption and jet. This is also a dominant negative-polarity coronal-hole region. For this jet we do not have XRT coverage, so in Figure 5 we only show an AIA 94 Å image during the mini-filament eruption. The white arrow in (Figure 2). After 15:04 UT, the mini-filament is completely ejected and becomes a part of the jet spire (Figure 1(c) and MOVIE1a). The mini-filament moves outward with an average speed of 105 ± 30 km s⁻¹. During the rise of the mini-filament, external brightenings start to appear at the far side of the majority-polarity (negative) flux clump. The AIA hotter channels (e.g., 94 Å) and XRT images also show the signature of external brightenings at the majority-polarity negative flux clump (Figures 1(b) and 2). This situation is broadly consistent with the polar coronal jet observations and schematic picture of Sterling et al. (2015). The magnetic evolution of this jet is shown in Figure 3, and will be discussed in Section 4.

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The pre-jet minifilament was seen to be at this neutral line for more than \(\sim 12\) hr. A noticeable rising of the minifilament body is underway at 02:05 UT. After that, the minifilament erupts abruptly from the solar surface, with an average speed of \(65 \pm 1.5 \text{ km s}^{-1}\), and the JBP turns on. Figures 4(b) and 5 show that the JBP sits on the neutral line where the minifilament was rooted before the eruption. Within 10 minutes, the AIA 171 Å images show that the cool minifilament material has been completely ejected along a broad spire. Thus, this jet is consistent with the definition of “blowout jets” given by Moore et al. (2010, 2013). (The other jets of Table 1 are also consistent with being blowout jets.) This jet has the
largest jet-base width (22,500 ± 1500 km, Table 1) among the 13 jets. Moreover, a huge external brightening also appears at the (negative) majority-polarity flux clump (shown by the turquoise arrows in Figure 4(b) and yellow arrows in Figure 5). The magnetic evolution of this jet is shown in Figure 6, and will be discussed in Section 4.

4. Magnetic Flux Cancelation under the Minifilaments

Figures 1(d)–(f) present line-of-sight magnetograms of the jet J11 region: (d) ~6 hr before the eruption onset, (e) during the eruption onset, and (f) after the eruption onset of J11. The HMI magnetograms and movie (MOVIE1b) clearly show flux convergence and cancelation at the neutral line throughout the observation period.

To see the longer-term evolution of the magnetic flux quantitatively, we measure the (positive) minority-polarity flux of the jet region (J11) as a function of time in the white box region of Figure 1(d). Here, and with all our jets, we only measured the minority-polarity flux because it could be isolated to avoid flows of flux of the selected polarity across the boundaries of the box. Figure 3(a) shows the integrated magnetic flux curve as a function of time. It shows a trend of continuous decrease in the positive flux for ~6 hr, which is clear evidence of flux cancelation. The persistent flux cancelation at the neutral line finally triggers the minifilament eruption at 14:59 UT; the eruption time is indicated with the red dashed line in Figure 3(a). We note that in weak field regions, tiny grains of flux coalesce to make dense flux clumps; these likely are the cause of the small bumps in the flux curve (e.g., at 12:10 UT).

Figure 3(b) displays the magnetic field evolution of the jet region over a time period of ~8 hr, as a time–distance map of the magnetic field along the red dashed line of Figure 1(e). One can clearly see that the two polarities converge toward the neutral line and cancel each other. In addition, there are some weak flux clumps close to the neutral line (that are not visible in the time–distance map) where flux cancelation goes on throughout the time period (e.g., at 10:49, 11:47, and 12:24 UT in animation 1b). Apparently, this continuous flux cancelation destabilizes the field holding the minifilament, resulting in its eruption. This behavior is in agreement with the quiet-region jet eruptions presented by Panesar et al. (2016b).

We can see in Figures 3(a) and (b) that the flux continues to cancel even after the jet eruption; it goes on until the minority-polarity flux has completely disappeared. In cases where minority-polarity flux remains after a jet and continues to cancel, there is a possibility of reformation of the minifilament. For example, in jet J3 the eruption occurs at 09:54 UT, and after that flux continued to cancel, resulting in the reformation/reappearance of the minifilament at the same neutral line and a second eruption at 11:30 UT (the second jet eruption is not included in Table 1). The jetting stops only when the minority-polarity flux patch has fully canceled (Panesar et al. 2017).

Figure 6(a) shows the integrated negative flux curve as a function of time for jet (J1). In this case we have measured the negative flux that was embedded inside the white box region of Figure 4(e). There is a continuous drop in the negative flux, especially over 02:00–03:00 UT (Figure 6(a) and MOVIE2b), which is a clear indication of flux cancelation between the opposite-polarity flux patches. Similarly, the flux cancelation is apparent in the HMI time–distance flux map of Figure 6(b), leading to the minifilament eruption and jet onset at 02:11 UT (red dashed line of Figure 6).

4.1. Flux Reduction

Each of the 13 coronal jets clearly shows progressive flux cancelation, and this apparently triggers the minifilament eruptions leading to the jets. The opposite-polarity flux patches were seen to approach the neutral line beginning several hours (at least ~3–4 hr, in some cases more than 3–4 hr e.g., in jet J11) before the eruptions. In order to obtain an estimate of the flux reduction percentage for each eruption, we measured the average flux values 3–4 hr before the eruption and 0–2 hr after the eruption (Table 1). We find that the flux clumps cancel with a flux loss of 20%–75% from before to after the eruption. For quiet-region jets (Panesar et al. 2016b), the flux reduction was similar, 20%–60% from before to after the jet eruption.

We also calculated the average cancelation rate for our 13 events and found it to be ~0.6 × 10^{18} Mx hr^{-1}. We can compare this with the quiet-region jets of Panesar et al. (2016b) by revisiting the flux data of Panesar et al. (2016b). We examined flux plots of all events of Table 1 of that paper, using the same procedure as above and we find that the average cancelation rate is ~1.5 × 10^{18} Mx hr^{-1} for quiet-region jets.

In active-region jet eruptions the flux cancelation rate was higher, ~1.5 × 10^{19} Mx hr^{-1} (Sterling et al. 2017).

5. Summary and Discussion

We have examined the triggering mechanism of 13 on-disk coronal-hole jets. In each of the 13 events we find that a minifilament is present at a neutral line where the jet occurs, and that flux cancelation at that neutral line apparently triggers the minifilament eruption driving the jet. These observations confirm that on-disk coronal-hole jets behave similar to on-disk quiet-region jets, which are also seen to erupt due to continuous flux cancelation at a neutral line underneath a minifilament that erupts to drive them (Panesar et al. 2016b). Thus, the schematic proposed by Panesar et al. (2016b) is also valid for the coronal-
hole pre-jet mini filament eruptions because the overall idea is the same.

Figure 7 shows an embellished version of the schematic from Panesar et al. (2016b) for the trigger of quiet-region pre-jet mini filament eruptions. A minority-polarity (negative field) flux patch resides in the dominant majority-polarity (positive) flux region and a mini filament (shown in blue color) sits at the neutral line of a small bipole (right side). The small (explosive) bipole contains a highly sheared and twisted field that holds the cool mini filament material. In Figure 7(a), the minority-polarity and majority-polarity flux patches are well separated from each other, as in the HMI magnetograms well before the jet occurrence (Figures 1 and 4). But flux cancelation is already occurring continuously among weak flux grains that are closer to the neutral line (this is the embellishment of the schematic of Panesar et al. 2016b) than are the large flux patches. Eventually, the large flux patches also start to converge, and the continuous flux convergence and cancelation at the neutral line eventually destabilizes the field that carries the mini filament material and it erupts outward. This drives the internal reconnection (lower star in (b) and (c)) that occurs in the legs of the erupting mini filament field, forming a JBP (low-lying red loop in (b) and (c)). The JBP appears at the location of the mini filament before the eruption (also see Figures 2 and 5). The outer envelope of the erupting mini filament field undergoes driven reconnection (known as external/interchange reconnection) with the impacted oppositely directed open (or far-reaching) coronal field lines (upper star in (b) and (c)). The external reconnection produces two new magnetic connections: the red closed loop over the large bipole in (c) and the red open field line in (c). Hot material (heated in the reconnection process) and cool mini filament material escape along the newly reconnected open field lines and appear as the jet spire. The EUV and X-ray images also show the signature of external...
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ORCID iDs

Navdeep K. Panesar @ https://orcid.org/0000-0001-7620-362X
Alphonse C. Sterling @ https://orcid.org/0000-0003-1281-897X

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The uncertainty was misstated in Panesar et al. (2016b) as ±600 km; the correct value is 5000 km.