Coronal Jets, and the Jet-CME Connection

Alphonse C. Sterling
NASA/ Marshall Space Flight Center, Huntsville, AL, 35806, USA
E-mail: alphonse.sterling@nasa.gov

Abstract.
Solar coronal jets have been observed in detail since the early 1990s. While it is clear that these jets are magnetically driven, the details of the driving process has recently been updated. Previously it was suspected that the jets were a consequence of magnetic flux emergence interacting with ambient coronal field. New evidence however indicates that often the direct driver of the jets is erupting field, often carrying cool material (a “minifilament”), that undergoes interchange magnetic reconnection with preexisting field ([1]). More recent work indicates that the trigger for eruption of the minifilament is frequently cancelation of photospheric magnetic fields at the base of the minifilament. These erupting minifilaments are analogous to the better-known larger-scale filament eruptions that produce solar flares and, frequently, coronal mass ejections (CMEs). A subset of coronal jets drive narrow “white-light jets,” which are very narrow CME-like features, and apparently a few jets can drive wider, although relatively weak, “streamer-puff” CMEs. Here we summarize these recent findings.

1. Introduction
Coronal jets are transient, long and relatively narrow features seen in EUV and X-ray images that shoot out from the solar surface and into the corona. While there were a smattering of earlier observations [2], jets were first studied in great detail with the Soft X-ray Telescope (SXT) on the Yohkoh spacecraft, launched in 1991. Because it was relatively sensitive to comparatively hot coronal emissions, the jets that appeared in the vicinity of active regions tended to be easiest to detect [3, 4]. SXT observations found jets to reach lengths of $1.5 \times 10^4$ km [4], and temperatures to range over $3 \text{ MK} - 8 \text{ MK}$ with an average of $5.6 \text{ MK}$ ([5]).

Launched in 2006, the Hinode satellite carries the X-Ray Telescope (XRT), which is sensitive to comparatively cooler coronal plasmas than was SXT; in particular, it is sensitive to emissions of $1 \text{ MK} - 2 \text{ MK}$, a characteristic temperature range for many coronal hole jets ([6, 7]). XRT found jets to be plentiful in polar coronal holes [8]; according to [9], jets occur at a rate of about 60 day$^{-1}$ in the two polar coronal holes, have lifetimes of $\sim 10$ min, lengths of $50,000$ km, and widths of $8,000$ km.

A jet consists of a spire, which extends into the corona, and a base region that is generally much brighter than the spire. Moreover, the brightest part of the base is often positioned asymmetrically with the spire, being located off to one side of the base region. These jet-base brightenings (hereafter, JBP, following [1]) have long been suspected as holding a clue to the cause of jets ([3]; also see [10]).
2. The Cause of Coronal Jets

It was quickly realized that the energy source for jets was likely magnetic. Magnetic field that permeates the solar atmosphere is fed by new magnetic flux that almost continuously “bubbles up” (i.e. emerges) through the photospheric surface. Upon reaching the surface, this emerging field spreads horizontally on the surface and expands outward into the higher atmosphere. An early suggestion was that jets resulted when flux emerging in this manner into the chromosphere and low corona runs into nearby pre-existing magnetic field in those regions. Interactions between the two flux systems would result in magnetic reconnection, at the interface between the emerging bipole and the pre-existing (e.g. open) field. According to this emerging-flux model, this reconnection would result in a small closed magnetic loop field, and also new open magnetic field, where the new closed loop would form the JBP and the jet spire plasma would flow out along newly open field.

New studies became possible with the launch of the Solar Dynamics Observatory (SDO) satellite in 2010. Its Atmospheric Imaging Assembly (AIA) instrument images the Sun in multiple full-disk EUV and UV wavelengths ([11]) at 12 s cadence (in the EUV bands) and with 0.6″ pixels, allowing for a much broader range of coverage of jet emissions than was possible with the X-ray instruments alone (both SXT and XRT had somewhat lower resolution than AIA, and variable cadences and fields of view). Also critical for jet studies is SDO’s Helioseismic and Magnetic Imager (HMI), which takes full-disk line-of-sight magnetograms at a cadence of 45 s, among other capabilities ([12]). Using these instruments and other resources, several jets were observed on the solar disk. They frequently showed the jets to emanate from locations where flux cancelation was occurring, without emergence (e.g., [13, 14, 15, 16, 17]). In some cases emergence was seen at the base locations of jets, but usually in conjunction with flux cancelation (e.g., [18, 19]). Some pre-SDO observations also showed emergence occurring together with cancelation at jet bases ([20]). Therefore it seemed that flux emergence was not essential for jet formation.

Using AIA EUV images, [17] found that a jet they observed appeared to form as the result of an eruption of a small-scale filament, which they called a minifilament, and that the JBP was a miniature flare that occurred in conjunction with eruption of the minifilament. In an extensive study of 20 randomly selected near-limb jets, [1] verified that the minifilament picture holds generally. They concluded that at least many (if not all) jets are a miniature version of the familiar full-scale eruptions that include an erupting filament, a solar flare, and often a coronal mass ejection (CME). Although their data were too near the limb for reliable comparisons with magnetograms, they argued that, on balance, the existing studies suggested that flux cancelation was often crucial to jet occurrence.

To investigate this further, [21] and [22] studied substantial numbers (~10) of on-disk jets, respectively in quiet Sun and coronal holes. For all of those examined jets, they found that cancelation occurred at the base of the jets. In some of those cases, flux emergence was also occurring, but in those cases the jet occurred at the neutral line where one pole of the emerging flux was canceling with pre-existing opposite-polarity field; this was also found by, e.g., [23] and [14]. Thus this strongly supports that magnetic flux cancelation is the trigger for onset of at least many jets. Moreover, for the jets of the quiet region study ([21]), the study of [24] found that the minifilaments that erupted to cause the jets also formed via flux cancelation, between about two hours and two days prior to the jet occurrence ([24]).

In the case of active regions ([25, 26]), the situation is not as clear cut. One reason is that minifilaments are sometimes but not always visible in the lead up to the jets. And secondly, the evolutionary magnetic changes are very rapid in the jetting locations, often with both flux cancelations and flux emergence occurring either concurrently or within a short time of each other. Nonetheless, all but one of several active region jets studied in [25] and [26] clearly occurred at the site of flux cancelation; one event of [25] was unclear in this regard. [26]
Figure 1. Schematic showing the minifilament eruption model for coronal jets; originally presented in [1], this version is from [30]. (a) A minifilament (blue disk) is in a magnetic bipole M2-M3, adjacent to a larger bipole M1-M2 (this is a 2D cut of a 3D negative-polarity background region with an intruding positive-polarity source at M2). The looped field line encircling the minifilament indicates non-potential twist in the field holding the minifilament. (b) The minifilament erupts, running into and undergoing interchange reconnection with opposite-polarity open (or far-reaching) field, leading to new field lines (dotted) including new open field that guides a hot jet (shaded region), and with field below the minifilament reconnecting “internal reconnection” [1]) and forming the JBP (thick red semicircle). (c) As the minifilament eruption progresses, eventually the interchange reconnection erodes the minifilament field, releasing the cool minifilament material to travel outward along the jet spire. See [1, 25, 26, 27] for more details. This picture has been modeled numerically by [31].

considers possibilities for why minifilaments are not always seen in active region events; these reasons include that pre-eruption minifilaments might be obscured by surrounding material, or in some cases a flux rope might erupt without a cool-material minifilament, as is the case with some large-scale eruptions.

Figure 1 summarizes several basic aspects of the view put forth for coronal jets in recent studies by the author and his colleagues ([17, 1, 25, 26, 21, 24, 27]).

(This team’s earlier work pointed out two “flavors” of jets: “standard” and “blowout” ([28, 29]). While the observational aspects of those jets are described appropriately in those two papers, that was prior to our findings on the connection between minifilament eruptions and jets. Therefore we have revised our view on the cause of standard and blowout jets; the updated description is presented in [1] and [27].)

3. Jets and CMEs
Given the evidence that coronal jets are miniature versions of CME-producing large-scale eruptions, one might expect that jets could also result in some version of CMEs. Indeed ejections visible in visible-light coronagraph images that originate from coronal jets have been detected. These coronagraph-imaged features seem to be of two basic types: narrow events and (somewhat) broader events, in reference to the heliocentric angle subtended by the ejected feature.

Narrow coronagraph-imaged ejections have been called “narrow CMEs” by some workers (e.g. [32, 33, 25]), while other workers refer to them as “white-light jets” ([34, 35]). Depending on the study, the observed events were of width $\lesssim 10^\circ$ or $\lesssim 15^\circ$, and so in either case of much smaller angular size than that of the average (non-halo) CME of $\sim 44^\circ$ ([36]). Other observations showing narrow CMEs and/or a jet-CME connection include [37, 38, 39, 13] and [18].

In addition to white-light-jet CMEs, somewhat broader CMEs can also result from jets
In these cases, the jets occur in the base region of the location that eventually erupts outward as the CME. In the cited studies, the base regions of the CMEs are bipolar active regions, and the jets occur along one edge of the active regions. These active regions form the bases of streamer structures that extend far into the corona, and the ejected CMEs travel outward along the streamers. These CMEs tend to be weak in intensity compared to the coronagraph-bright streamer, and the CMEs do not totally disrupt the streamer; for these reasons we refer to these events as “streamer-puff” CMEs ([38]). For the six streamer-puff events analyzed in [40], widths ranged over $25^\circ - 50^\circ$. Thus they are somewhat broad; broader than the above-mentioned narrow CMEs ($< 15^\circ$), but only reaching about the above-mentioned average width for general CMEs ($\sim 44^\circ$).

There is evidence that both of these types of CMEs are driven by the jets, but the driving mechanism differs between the two. Moreover, a key component to the driving appears to be non-potential magnetic twist contained in minifilaments, where the twist either is added to the minifilament as it is in the process of erupting to form the jet, or the twist exists on the minifilament prior to its eruption (in which case more twist might be added during eruption); Figure 1 shows schematically this twist on the minifilament.

Regarding the mechanism in narrow CMEs, [42] found that the jets that formed such narrow CMEs all had a propensity to contain a relatively large amount of twist, compared to the average jet that did not make a (narrow) CME. The picture envisioned by [42] for these narrow CMEs is basically that of Figure 1, but where the reconnection in Figure 1(b) transfers a relatively large amount of twist onto the open field ([43]). That twist that has been added to the open field then helps propel the jet material far enough away from the Sun so that it can show enhanced density in SDO/LASCO C2 coronagraph images.

Regarding the mechanism for the streamer-puff CMEs, [38] provided an initial suggestion. That study however was prior to our new understanding about jets as expressed in the minifilament eruption model (Fig. 1). [40] now provides a revised view that supersedes the explanation given in [38]. According to [40], streamer-puffs result as shown in Figure 2; basically, the setup is as in Figure 1, but where the apparently vertical field is actually a part of a larger-scale loop, and that larger-scale loop forms the base region of a coronal streamer. Upon eruption, twist contained in the erupting minifilament is transferred to the larger-scale loop. That injected twist drives the larger-scale loop outward along the streamer, forming the streamer-puff CME.

4. In Closing

Much work has been done to advance our understanding of coronal jets over the past two decades since their (re)discovery with the Yohkoh satellite. Paper [2] reviews much of this progress. But that review was largely written during 2015, just as an understanding of a connection between minifilament eruptions and jets ([1]) was coming to the fore. Thus, in the author’s view, [2] under-emphasizes the importance of minifilament eruptions in jet production. Of course more studies are required to establish with certainty (or to challenge) this idea. Similarly, it now appears that the importance of flux cancelation in triggering jets ([15, 16, 21, 22, 25, 26]) has until recently been under appreciated.

There are still however some suggestions that jets can occur when there is flux emergence in the absence of cancelation, as argued by [44] for 6 of 20 events they studied (the remaining 14 events all clearly included cancelation). While we recognize that the Sun may choose to make jets in this fashion sometimes, we also caution that for jets near active regions, it can be difficult to isolate emergence from cancelation ([25, 26]). Because a large majority of jets are clearly triggered by cancelation in quiet Sun and coronal holes, where cancelation and emergence can be more easily differentiated ([21, 22]), one might expect cancelation to trigger almost all jets in active regions too. This, however, must be resolved by careful study of more jet events.

Finally, it is now clear that some jets can reach the outer corona and make ejections in the
Figure 2. Jet eruption driving a streamer-puff CME, from [40]. (a) A minifilament-field (with or without a cool minifilament) erupts as in Figs. 1(a) and 1(b) (see details in insert a1). In this case the minifilament (with a twisted-field magnetic envelope) erupts inside a larger-loop field (in Fig. 1(a), the corresponding field was either open or far-reaching; here is is “far reaching,” extending to the “+” on to the right of the erupting minifilament system). This larger loop is part of a loop system that forms the base of a surrounding and overlying streamer field. (b) Twist from the erupting-minifilament field is transferred to the larger loop. (c) This renders the larger loop unstable, causing it to erupt along the streamer to form the streamer-puff CME.

form of narrow CMEs or streamer-puff CMEs. There is even the thrilling possibility that some of this material might be observed in situ by the Parker Solar Probe, which in turn could tell us more about the nature of jets.

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