HOMOLOGOUS JET-DRIVEN CORONAL MASS EJECTIONS FROM SOLAR ACTIVE REGION 12192

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ABSTRACT

We report observations of homologous coronal jets and their coronal mass ejections (CMEs) observed by instruments onboard the Solar Dynamics Observatory (SDO) and the Solar and Heliospheric Observatory (SOHO) spacecraft. The homologous jets originated from a location with emerging and canceling magnetic field at the southeastern edge of the giant active region (AR) of 2014 October, NOAA 12192. This AR produced in its interior many non-jet major flare eruptions (X- and M-class) that made no CME. During October 20 to 27, in contrast to the major flare eruptions in the interior, six of the homologous jets from the edge resulted in CMEs. Each jet-driven CME (∼200–300 km s⁻¹) was slower-moving than most CMEs, with angular widths (20°–50°) comparable to that of the base of a coronal streamer straddling the AR and were of the “streamer-puff” variety, whereby the preexisting streamer was transiently inflated but not destroyed by the passage of the CME. Much of the transition-region-temperature plasma in the CME-producing jets escaped from the Sun, whereas relatively more of the transition-region plasma in non-CME-producing jets fell back to the solar surface. Also, the CME-producing jets tended to be faster and longer-lasting than the non-CME-producing jets. Our observations imply that each jet and CME resulted from reconnection opening of twisted field that erupted from the jet base and that the erupting field did not become a plasmoid as previously envisioned for streamer-puff CMEs, but instead the jet-guiding streamer-base loop was blown out by the loop’s twist from the reconnection.

Key words: Sun: activity – Sun: coronal mass ejections (CMEs) – Sun: flares

Supporting material: animations

1. INTRODUCTION

Active region (AR) NOAA 12192 contained the largest sunspot group to date of solar cycle 24.3 The interior of this AR produced a multitude of big X- and M-class flares as well as many B- and C-class flares during its passage across the solar disk from 2014 October 17 to 30. All of these interior flares were confined, i.e., they did not produce coronal mass ejections (CMEs) (Chen et al. 2015; Sun et al. 2015; Thalmann et al. 2015). The AR apparently produced a large fast CME on October 14, before it rotated onto the disk (West & Seaton 2015). During disk passage, it produced six “streamer-puff CMEs” (Bemporad et al. 2005), where the CME comes from a compact ejective eruption in a foot of one loop of a coronal streamer-base magnetic arcade and the streamer transiently bulges out, but is not blown away completely by the passage of the CME (Moore & Sterling 2007; Jiang et al. 2009). Only one of these CMEs, accompanied by an M4.0 flare, was previously reported (Chen et al. 2015; Li et al. 2015; Thalmann et al. 2015). They all originated from the southeastern edge of the AR from a series of coronal jets occurring at a neutral-line-containing subregion at that location, a neutral line separate from that of the AR-interior confined flares.

“Jets” are dynamic, transient, collimated features that become long compared with their width. Those with coronal emissions (“coronal jets”) occur in coronal holes, quiet regions, and ARs, and have a brightening at their base (e.g., Shibata et al. 1992; Shimojo et al. 1996; Sheeley et al. 1999; Cirtain et al. 2007; Nisticò et al. 2009). Our observed jets might also be referred to as “surges” (Zirin 1988). Jets are frequently described as occurring on open-field regions (coronal holes, or at AR-coronal-hole boundaries), whereas our jets here occur on relatively large-scale closed loops of an AR.

There are various definitions of CMEs (e.g., Sheeley et al. 2009; Vourlidas et al. 2013). Here we use the term to mean a coronal ejection that is listed in the LASCO CME catalog.4 In addition to the CME-producing jets, many other jets from the same subregion did not produce CMEs. Here we discuss the CMEs and the CME-producing jets, and differences between the CME-producing and the non-CME-producing jets. We then present our interpretation that the CMEs were driven by magnetic twist injected by the reconnection that made the CME-producing jets.

2. INSTRUMENTATION AND DATA

In our analysis we used EUV images and movies from the Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA) to study the jets, and we used images from the C2 coronograph of the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) onboard the Solar and Heliospheric Observatory (SOHO) to study the CMEs. LASCO/C2 shows the outer corona between 2 Rₚ and 6 Rₚ with a temporal cadence of 12 minutes (Brueckner et al. 1995). The SDO/AIA images have a cadence of 12 s and spatial resolution of 0″6 pixel⁻¹ (Lemen et al. 2012). We used primarily 304 and 193 Å images5 to view transition-region-temperature and coronal-temperature jet structures. We derotated all the AIA images to a particular time and created movies

4 http://cdaw.gsfc.nasa.gov/CME_list
5 http://jsoc.stanford.edu/ajax/exportdata.html
with relatively coarse temporal cadence (of one minute), which was sufficient for studying the jets’ evolution.

The X-ray Telescope (XRT) on Hinode had coverage of only three of our six CME-producing jets (J1, J2, and J5 in Table 1). Each of these three jets was clearly visible in the XRT images, so all six of our CME-producing AIA jets were probably X-ray jets having cooler EUV components.

We studied the photospheric magnetic field using SDO/Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) line of sight magnetograms, which have cadence of 45 s and spatial resolution of 0.5′ pixel−1 (Scherrer et al. 2012).

We found a total of six CME-producing homologous solar jets from AR NOAA 12192 between 2014 October 20 and 27. These ejective jets and CMEs were identified by looking at movies from JHelioviewer.6 Table 1(a) lists the six jets and corresponding CMEs. We also studied the properties of seven non-CME-producing jets of 2014 October 22; see Table 1(b).

### 3. OBSERVATIONS

Figure 3(c) shows the AR. The highly dynamic jetting location is on the southern edge of the AR (Figure 3(a)). This location produced six ejective eruptions, each of which produced a flare, jet, and CME (Table 1(a)). These jets have characteristics of blowout jets (Moore et al. 2010). These eruptions were reported in the Reuven Ramaty High-Energy Solar Spectroscopic Imager (RHESSI); Lin et al. 2002) flare list, as well as in the LASCO CME (see footnote 4) and NOAA flare catalogs.8

#### 3.1. Evolution of Jets and CMEs

Figure 1 shows three of the homologous jets observed by SDO/AIA. Figures 1(a)–(c) shows the progression of jet J2. The white arrows in Figure 1(a) point to brightenings in the base of the jet as the jet begins to rise. Later (in Figure 1(b)), the outward-moving jet spire extends higher in the corona (Figures 1(c) and 3(c)). The bright spire appears to extend along twisting magnetic field (e.g., at 16:58 UT in Figure 1(b); also see MOVIE304). The transverse-motion in Figures 3(d) and (f) (the insets) show definite twisting-motion tracks (traced by the blue lines). The upper part of (304 Å) jet J2 leaves the AIA field of view (FOV) at ~17:21 UT (MOVIE304), showing that the material exceeded a height of 6.1 × 10⁵ km (which is the plane-of-sky distance from the jet base to the edge of the AIA FOV along the jet’s path). After that the lower part of the jet fades away slowly and some of the jet material falls back to the solar surface (~18:26 UT). Figures 1(e)–(g) and (i)–(k), respectively, show example images of jets J4 and J5. We find that the jets recur and emanate from the same region and have similar structure and development; that is, they are homologous (Dodson-Prince & Bruezek 1977, pp. 81–96).

Figures 1(d), (b), and (l) show the remote brightening and/or dimming at the other end of the loop during the jet eruptions.

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### Table 1

| Jet No | Date (UT) | Time | Flare Class | CME Speedb,c (km s⁻¹) | CME Angular Width (°) | Jet Speedd (km s⁻¹) ± (±5 minute) | Jet Rise Dur. (±1500 km) | Jet Widthf | Remote Bri. and Dim. |
|--------|-----------|------|-------------|-----------------------|----------------------|-----------------------------------|--------------------------|-------------|---------------------|
| J1     | 20 Oct 14 | 18:43| C6.2        | 187                   | 40                   | 190 ± 10                         | 20                       | 34000       | Yes                 |
| J2     | 22 Oct 14 | 16:52| C5.8        | 281                   | 20                   | 310 ± 20                         | 30                       | 38000       | Yes                 |
| J3     | 23 Oct 14 | 19:11| C3.3        | 259                   | 35                   | 330 ± 20                         | 50                       | 26000       | No                  |
| J4     | 24 Oct 14 | 03:56| C3.6        | 250                   | 30                   | 360 ± 20                         | 45                       | 34000       | Yes                 |
| J5     | 24 Oct 14 | 07:37| M4.0        | 677                   | 35                   | 400 ± 40                         | 35                       | 86000       | Yes                 |
| J6     | 27 Oct 14 | 17:33| M1.4        | 186                   | 25                   | 76 ± 10                          | 35                       | 19000       | ...                 |

#### Notes.
- 6 ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/2014/
- 7 ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/2014/
- 8 ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/2014/
- http://cdaw.gsfc.nasa.gov/CME_list
- Uncertainty in the CMEs speed measurement is less than 10% (Yashiro et al. 2004).
- Measured at a projected height of ~72,000 km from jet base.
- This jet shows up well in the AIA 94 Å images, but not in 304 Å images. Due to its poor visibility in 304 Å images, we were unable to follow the jet plasma well enough to measure its speed.
- AR was close to the west limb, obscuring any remote brightening/dimming.
- Slower velocity (250 km s⁻¹) in the beginning, but faster (>650 km s⁻¹) later when a plug of plasma separates.
We discuss the brightenings in Section 4. The dimmings support that the loop is ejected as the CME. Such far-end brightenings and dimmings are not discernible in J3 (Table 1), but that event is weaker than the others.

In Figures 2(a)–(c), we show the CME corresponding to jet J2 (Figure 2(a) and MOVIECME). There is no indication of the CME (Figure 2(a)) while the jet is still in the AIA FOV. However, as soon as the jet moves beyond the AIA FOV, the
preexisting coronal streamer starts to inflate (see the non-difference LASCO movie\textsuperscript{9}) as the CME is developing. Figure 2(b) shows the early phase of the CME when the jet was still escaping from the AIA FOV. After that, the CME continued to expand and escape, and definitely shows twisted structure and untwisting motion (MOVIECME). Our other streamer-puff CMEs show less definite evidence of twist in the LASCO C2 running-difference movies (see footnote 4). The streamer was not blown out by the passage of the CME, only disturbed (i.e., transiently inflated). Figures 2(d)–(f) and (g)–(i), respectively, show the CMEs from jets J4 and J5. These jet-driven CMEs had relatively narrow angular widths (20°–50°; see Table 1(a)), comparable to that of the streamer base (∼40°). The second CME observed on 2014 October 24 (from Jet J5) had the largest angular width (Figure 2(i)) of the CMEs of Table 1(a).

\textbf{3.2. Jet and CME Speeds}

All six CME-producing jets contain substantial transition-region (304 Å) emitting material. We measured the plane-of-sky speeds of the jets as they erupted and flowed outward (Table 1). We take a straight line along the main axis of the jet

\textsuperscript{9} http://lasco-www.nrl.navy.mil/daily_mpg/2014_10/
Figure 3. Jet outflow and spin: (a) HMI line of sight magnetogram of AR 12192; (b) The jet-producing region (white box of a); (c) AIA 304 Å intensity image of jet J2; and (e) jet J5 of Table 1. The white lines in (c) and (e) mark the positions of the time–distance plots in (d) and (f), respectively. Panels (d) and (f) show AIA 304 Å intensity height-time-series images along the vertical lines in panel (c) and (e), respectively. Insets in (d) and (f) show the 193 Å intensity timeseries images along the blue lines in panel (c) and (e), respectively; they show changes consistent with jet twisting with time. The green dashed arrows in (d) and (f) are the paths used to calculate outflow speeds of the plasma. The x-axis of (a) is the same as (c).

(An animation (c) of this figure is available.)
in 304 Å (Figure 3(c)) to construct a height–time plot. Figure 3(d) shows the plot for jet J2 along the white fiducial line in Figure 3(c). It shows a bright outward flow of plasma starting at ~16:52 UT. The total duration of this jet is about 30 minutes. Plasma was propelled high into the corona (Figure 3(d) and MOVIE304); only a small fraction appears to fall back to the solar surface, while most material flowed out of the AIA FOV (similarly, the other five jets of Table 1(a) largely left the AIA FOV). The slope of the green dashed arrow in Figure 3(d) gives 310 km s$^{-1}$ for the upflow speed of jet J2.

Figure 3(d) shows another enhanced brightening beginning at 17:32 UT, which is due to a subsequent jet that was not centered on the white line of Figure 3(c). This was a non-CME-producing jet (J12; Table 1(b)). One can see in MOVIE304 that plasma from this jet does not reach as high as the earlier jet (J2). The material of jet J12 mainly becomes trapped in closed field lines.

Figure 3(e) shows jet J5, the largest jet of our data set, which erupts in conjunction with an M4.0 flare. Figure 3(f) shows the height–time plot along the white fiducial line of Figure 3(e). This jet is much broader than the other jets shown in Table 1(a) and had a plane-of-sky speed of about 400 km s$^{-1}$ along the white line (the slope of the green dashed arrow). This jet produced a CME with plane-of-the-sky speed of 680 km s$^{-1}$, twice that of the CME from jet J2. Speeds of all CME jets and widths of both categories of jets (Tables 1(a), (b)) are similar (mean duration and weighted standard deviation are 35 and 10 minutes, respectively) than the non-CME-producing jets (18 and 9 minutes, respectively); and (d) the CME-producing jets are wider (mean width and weighted standard deviation are 43,000 and 24,000 km, respectively) than the non-CME-producing jets (15,000 and 2700 km, respectively). Our jet-driven CMEs are slower (speed ~300 km s$^{-1}$) than average CMEs with flares (>750 km s$^{-1}$, e.g., Seeley et al. 1999).

Our CMEs result from jet eruptions. Recently it has been found that jets in coronal holes are driven by minifilament eruptions (Sterling et al. 2015). The minifilaments reside in presumably twisted magnetic field in the core of a small bipole between ambient open field and the minority-polarity side of a larger bipole. The minifilament-carrying bipole erupts and reconnects with the open field, producing the jet. It is plausible that our AR jets here operate the same way as Sterling et al. (2015) coronal hole jets (see Li et al. 2015). We further speculate that our jets lead to the CMEs as follows. During the reconnect, twist of the erupting minifilament field is transferred to the newly-reconnected open field (Shibata & Uchida 1986; Pariat et al. 2009; Török et al. 2009; Archontis & Hood 2013; Fang et al. 2014; Moore et al. 2015). Because our AR jet eruptions occur in the foot of one loop of the streamer-base arcade, only that loop gets blown out rather than the whole arcade and whole streamer, and thus results in a streamer-puff CME (Bemporad et al. 2005).

Figure 4 shows a schematic of this proposed process based on our observations. The jet-producing region (the dashed box in Figure 4(a)) is embedded in the outskirt of the overall arcade of loops of the AR and inside the arcade base of a LASCO-observed large streamer. Based on Sterling et al. (2015) and because there is cool transition-region plasma in our jets, we assume that the jet-producing region (Figures 4(a) and (a1)) includes a sheared field that contains a minifilament (Li et al. 2015 confirm that at least one of the jets of this region originates as an erupting (mini)filament). And as we observe spinning motion in our jets, we further assume that the minifilament resides in twisted field (e.g., Moore et al. 2015). Following the schematic of Sterling et al. (2015), we envision that at the start of the jet the minifilament-holding field erupts, and undergoes two forms of magnetic reconnection: (1) internal reconnection among the legs of field inside of (i.e., internal to) the erupting minifilament field (the lowest star in Figure 4(a1)) that makes bright flare ribbons and loops at the jet base (shown as the jet base left-hand side small magenta loop in Figures 4(b) and (c)), and (2) external reconnection (the highest star in Figure 4(a1)) of the erupting minifilament field with a loop of the big arcade that is external to the minifilament field. This external reconnection (1) makes the jet base right-hand side small magenta loop in Figures 4(b) and (c), and (2) transfers twist from the erupting field to the reconnecting big loop (red twisted lines in Figure 4(b)). We observed remote brightenings and dimmings at the far end of the erupting-CME loop (Figures 1(d), (h), and (l) and Table 1), consistent with this picture; the brightenings are from high-speed electrons that are accelerated by the external reconnection, escape along the big loop, and impact the far-end lower atmosphere (e.g., Tang & Moore 1982), and the dimmings are due to the big-loop blowout (e.g., Moore & Sterling 2007). During the eruptions only one segment of the outer streamer arcade gets ejected rather than the whole coronal streamer arcade because the jet eruptions occur in the foot of only one loop of the arcade.
added magnetic pressure from the added twist drives the arcade loop out to become the streamer-puff CME; that is, the twist-loaded magnetic loop of the streamer base (Figure 4(c)) erupts to become the streamer-puff CME. After each eruption the opened field presumably recloses by reconnection, which allows the series of CMEs from the homologous jets (Sterling & Moore 2001; Panesar et al. 2015).

The non-CME-producing jets are weaker, and apparently do not transfer enough twist to the streamer-base loop to blow it out as a discernible streamer-puff CME.

This picture of streamer-puff CMEs differs from that of Bemporad et al. (2005). They proposed a scenario whereby a flux-rope plasmoid explodes up the leg of the loop of the streamer-base arcade from a compact ejective flare eruption and explodes the loop top outward to become the streamer-puff CME (Bemporad et al. 2005; Moore & Sterling 2007; Jiang et al. 2009). We propose that the CMEs are driven by the helicity loaded onto the magnetic-arch loop from the erupting minifilament field as the jet forms, rather than by an erupting plasmoid as suggested by Bemporad et al. (2005).

High-quality AIA data were not available for the events of Bemporad et al. (2005). We have since learned that many jets result from minifilament eruptions (Sterling et al. 2015), so we suspect the jets we observe here occur that way also. Moreover, AIA images of our events here show no indication of an erupting plasmoid (which would appear as a largely intact closed-loop flux-rope structure; see Figures 3(b) and (c) of Bemporad et al. 2005). Rather, apparently the minifilament field is entirely opened by the external reconnection and ceases to be a plasmoid early in the jet-formation process (Figures 4(a), (a1), and (b)), having become new big-arch field in the jet and new closed loops in the jet’s base (Figures 1(b), (f), and (j)). Therefore, at least for the events presented here, the Figure 4 schematic explains the streamer-puff phenomenon better than does the schematic of Bemporad et al. (2005).

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