An EUV Jet Driven by a Series of Transition Region Microjets

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Abstract

Jets are one of the most common eruptive events in the solar atmosphere, and they are believed to be important in the context of coronal heating and solar wind acceleration. We present an observational study on a sequence of jets with the data acquired with the Solar Dynamics Observatory and the Interface Region Imaging Spectrograph. This sequence is peculiar in that an extreme-ultraviolet (EUV) jet, ~29″ long and with a dome-like base, appears to be a consequence of a series of transition region (TR) microjets that are a few arcseconds in length. We find that the occurrence of any TR microjets is always associated with the change of geometry of microloops at the footpoints of the microjets. A bundle of TR flux ropes is seen to link a TR microjet to the dome-like structure at the base of the EUV jet. This bundle rises as a response to the TR microjets, with the rising motion eventually triggering the EUV jet. We propose a scenario involving a set of magnetic reconnections, in which the series of TR microjets are associated with the processes to remove the constraints to the TR flux ropes and thus allows them to rise and trigger the EUV jet. Our study demonstrates that small-scale dynamics in the lower solar atmosphere are crucial in understanding the energy and mass connection between the corona and the solar lower atmosphere, even though many of them might not pump mass and energy to the corona directly.

Unified Astronomy Thesaurus concepts: Solar coronal transients (312); Solar corona (1483); Active solar corona (1988); Solar transition region (1532); Solar magnetic reconnection (1504); Plasma jets (1263); Solar atmosphere (1477)

Supporting material: animations

1. Introduction

Jets are one of the most common features in the solar atmosphere, and are thought to be essential phenomena to understand the problems of coronal heating and solar wind acceleration (Raouafi et al. 2016). They are widely observed in the solar atmosphere (Shen 2021), with sizes ranging from several to several hundred megameters. In the corona, jets are transient plasma ejection aligned with magnetic field lines such as open fields or large loops. There are two types of coronal jets, straight anemone jets and two-side-loop jets (Shibata et al. 1994a). They have been observed in X-rays and almost all extreme-ultraviolet (EUV) wave bands (e.g., Shibata et al. 1992; Shimojo et al. 1996; Nistico et al. 2009; Huang et al. 2018), and this demonstrates their multithermal nature. Observations have also shown that the hot components of a coronal jet are associated with heating by magnetic reconnection between local closed and open magnetic fields, while the cool components are from the small eruptive filaments under a jet’s base arch (Shen et al. 2012). The impulsiveness and energetics of a jet could be predicted through its surrounding magnetic field configuration via a model given by Pariat et al. (2015).

Straight anemone jets normally appear as a cusp shape (Liu et al. 2011), fan-spine structure (Zeng et al. 2016), inverted-Y (Nelson et al. 2019), or quasi-circular ribbon (Jiang et al. 2015). Magnetic structures of the footpoints of straight anemone jets are normally mixed polarities (Shen 2021). Using the latest Solar Orbiter observations, Hou et al. (2021) point out that the footpoints of most coronal microjets occurring at the edge of networks are related to concentrations of magnetic flux and mixed polarities. Pariat et al. (2010) show that the magnetic characteristics of a jet could determine its dynamics, such as twist, size, symmetry, and null points. Wyper & DeVore (2016) demonstrate that the dynamics of a jet are sensitive to the ratio of the width of its source region to the footpoint separation of the enveloping loops.

Straight anemone coronal jets are thought to be produced by magnetic reconnection between emerging bipoles and local open fields (Yokoyama & Shibata 1995; Shen et al. 2011; Huang et al. 2012; Yan et al. 2015). Both a chromospheric surge and X-ray jet can be generated simultaneously from the same magnetic reconnection between rising loops and local open fields that also release enough energy to produce microflares (Yokoyama & Shibata 1995). When reconnection occurs between local close field and open field, magnetic field lines reconnect to the ambient ones, and form a jet whose base appears to be a structure like an anemone (Shibata et al. 1994b; Chen et al. 2015). Based on magnetic extrapolation and observing characteristics from EUV, UV, X-ray data, the typical magnetic topology of a jet has been found to include a 3D null point that is associated with an embedded dipole and shows as a dome-like or inverted-Y shape (e.g., Lau & Finn 1990; Fletcher et al. 2001; Pariat et al. 2009, 2015; Liu et al. 2011; Zhang et al. 2012; Moreno-Insertis & Galsgaard 2013; Wyper et al. 2017). The dome could be destroyed by magnetic reconnections between emerging flux ropes and the fan-spine dome (Jiang et al. 2015).
In observations of most straight anemone jets, the rising and eruptions of minifilaments below the dome seem to be essential (Sterling et al. 2015; Hong et al. 2017; Li et al. 2017, 2018a; Xu et al. 2017; Li et al. 2018b; Li & Yang 2019). The minifilament could be formed due to a strong sheared magnetic field, and a decrease in the constrain force can lead to its rising thus resulting in reconnection with a local open field, and the production of jets (Wyper et al. 2017). Kumar et al. (2018) suggest that the free energy supplied to jets comes from magnetic shear motion at the polarity inversion lines, and these activities are consistent with a breakout model. By studying pseudostreamer jets and coronal mass ejections (CMEs), Kumar et al. (2021) find that the determining factor to the dynamic behavior of an eruption is the ratio of the magnetic free energy related to the filament channel compared to the energy of the overlying flux both inside and outside the pseudostreamer dome. Wyper et al. (2016) suggest that the filamentary structure caused by repeated tearing-like instability in magnetic reconnection provides an explanation for intermittent outflows and brightening blobs in jets that have been reported by many studies (e.g., Zhang & Ji 2014; Chen et al. 2022). Zhang & Ni (2019) further confirm that blobs can originate from the tearing instability occurring at the base of a coronal jet or inside a coronal jet. A recent simulation based on a spheromak configuration demonstrates that magnetic reconnection at the bottom of the spheromak due to emerging processes is the reason for the onset of a coronal jet (Latham et al. 2021).

Nishizuka et al. (2008) find evidence of propagating Alfvén waves along the jet, which are produced by magnetic reconnection in the transition region (TR) or upper chromosphere. Moore et al. (2015) suggested that the driver of a jet can be magnetic-untwisting waves, which are large amplitude torsional Alfvén waves generated in magnetic reconnection and that may dissipate in the corona. In a dome model, when stress is applied at the photosphere, a 3D null point topology will be driven by a continuously twisting motion, and the helical rotating current sheet located along the fan between the sheared spines can naturally produce jets (Pariat et al. 2010). MHD waves, nonthermal electrons, or a conduction front associated with a coronal jet can heat the far end of the coronal loop along which the ejecting plasma is flowing (e.g., Shimojo et al. 2007; Huang et al. 2020).

Coronal jets might occur sequentially or with multiple phases. Zhang et al. (2021) report a flare-related coronal jet and find its slow rising phase is caused by reconnection at the breakout current sheet and its fast rising phase is caused by reconnection at the flare current sheet. Shen et al. (2012) report a simultaneously produced bubble-like CME and jet-like CME with two steps including reconnection between the open field and the filament channel, and under the filament channel. Tang et al. (2021) find that the open field reconnected in the occurrence of the first jet sweeps and reconnects with other coronal bright points and thus produces the second jet. Sterling et al. (2017) suggest that the rising minifilaments reconnect with the dome at different positions several times and this produces multiple jets in one dome system.

Although coronal jets have been studied for decades and many key aspects have been understood, their connection to abundant small-scale activities in the lower solar atmosphere has been poorly investigated. In this paper, we report on multiwavelength imaging and spectroscopic observations of a sequence of jets including an EUV jet, a series of TR microjets, and a bundle of TR flux ropes. We will investigate in-depth the evolution of these jets and demonstrate what roles those TR microjets play in driving the relatively large EUV jet. In what follows, we give the data description in Section 2, results in Section 3, discussion in Section 4, and conclusions in Section 5.

2. Observations

Our data were obtained on 2016 June 2 from 09:16:39 UT to 10:28:55 UT with a target of AR 12551, by the space-borne Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Helioseismic and Magnetic Imagers (HMI; Scherrer et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012) and the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014). The data analyzed in this study mainly include the line-of-sight magnetograms taken with the HMI, images at the AIA EUV passbands of 94 Å, 171 Å, 304 Å, and UV passband of 1600 Å, images with the IRIS slit-jaw imager (SJI) at the passbands of 1400 Å and 2796 Å and spectral data with the IRIS spectrograph.

The pixel size of the HMI magnetograms is 0.66, and the cadence is 45 s. The AIA data have a pixel size of 0.67 and a cadence of 12 s for EUV images and 24 s for images at 1600 Å passband. The IRIS SJ images have a 0.17 pixel size and 18 s cadence. Both HMI and AIA data have been reduced by the standard procedure of aia_prep.pro in solarsoft. The level 2 IRIS SJ data are used, and no further calibration is required.

The IRIS spectrograph was running in a “sit and stare” mode with 9 s exposure time from 09:16:39 UT to 10:29:04 UT. In total, it obtained 468 exposures with a cadence of 9.3 s. The spectrograph slit has a width of 0.35 and the data downloaded here cover 119″ along the slit. The relative location of the spectrograph slit is shown in Figure 1(a) as the dark vertical line. In this study, we analyze the spectral data of Mg II (1.4 × 10^5 K), C II (2.5 × 10^3 K), Si IV (7.9 × 10^3 K), and O IV (1.4 × 10^5 K). The pixel sampling of the wavelength is about 25 mA pixel^-1. The production of the spectral data is level 2, from which we have applied the radiometry calibration by following the procedures given in the user’s guide provided on the IRIS official website.

The images from different passbands and/or instruments have been co-aligned by using multiple reference structures (such as dark and bright points) in passbands with the closest representative temperatures.

3. Results

The sequence of the events occurs near the west limb from 09:16 to 09:50 UT (see Figure 1 and the associated animation). They consist of a series of microjets and a large jet. The large jet with an inverted-Y shape originates from a dome-like feature (pointed by the white arrow in Figure 1(a)). Please note that the dome-like feature is only visible when the jet occurs. The large jet can be seen at coronal as well as transition region temperatures (see the elongated feature denoted by cyan arrows in Figure 1). The series of microjets originate from a block of bright points toward the north of the dome-like feature, and in contrast to the large jet they can be seen only in the IRIS SJ 1400 Å (i.e., transition region). In Table 1, we list a number of key parameters of the large jet and these microjets. By investigating these observations in-depth, we suggest that these...
microjets modify the magnetic topology that drives the large jet. More details are given in the following.

### 3.1. Properties of the Large Jet

The large jet starts at 09:38 UT and lasts for about 10 minutes. It has a curved trajectory, implying that it may flow along a large magnetic loop. The jet can be seen in all the IRIS SJ and AIA EUV passbands (see the cyan arrows in Figure 1, where not all passbands are shown). The brightenings at the base of the jet as viewed in these passbands peak at almost the same time and thus we cannot distinguish which one has its first response. In the SJ 1400 Å passband, it consists of a

![Figure 1](image-url)

**Figure 1.** The region of interest observed in the IRIS SJ 1400 Å (a) and AIA 304 Å (b), AIA 171 Å (c), AIA 94 Å (d) passbands. The black dotted lines in panel (a) outline the field of view shown in Figure 5. The white arrow in panel (a) denotes the dome-like feature. The green diamond symbols in panel (a) outline the trajectory of the EUV jet, which is also marked by the cyan arrows in the others. The black vertical line in panel (a) is the location where the slit of the IRIS spectrograph targets on, and the white dashed line indicates the spatial range where the slit images are shown in Figures 3 and 4. An associated animation is given online. The animation includes evolution of this field of view seen in the four passbands from 09:16:39 UT to 10:28:55 UT. The real-time duration of the animation is 16 s.

(An animation of this figure is available.)

### Table 1

Physical Parameters of the Sequences of Jets

| Jet         | Start Time (UT) | Location* (X″, Y″) | Length* (″) | Width* (″) | Speed* (km s⁻¹) | Lifetime (s) | Density (10¹¹ cm⁻³) | Passbands* (Å) |
|-------------|-----------------|---------------------|-------------|------------|-----------------|--------------|---------------------|----------------|
| Large jet   | 09:38:03        | 917.1,85.6          | 29 ± 0.34   | 4 ± 0.34   | 175 ± 35        | 600 ± 18     | 1.5 ± 0.3           | 1400+EUV       |
| 1st microjet| 09:17:17        | 917.5,90.0          | 4.6 ± 0.34  | 0.7 ± 0.34 | 47 ± 10         | 90 ± 18      | ...                 | 1400           |
| 2nd microjet| 09:19:08        | 916.5,93.1          | 3.3 ± 0.34  | 0.8 ± 0.34 | 59 ± 22         | 54 ± 18      | ...                 | 1400           |
| 3rd microjet| 09:22:39        | 916.4,92.8          | 6.3 ± 0.34  | 0.7 ± 0.34 | 50 ± 9          | 90 ± 18      | ...                 | 1400           |
| 4th microjet| 09:26:39        | 917.6,90.9          | 8.0 ± 0.34  | 0.6 ± 0.34 | 64 ± 11         | 70 ± 18      | ...                 | 1400           |
| 5th microjet| 09:30:15        | 917.6,89.9          | 3.0 ± 0.34  | 0.6 ± 0.34 | 67 ± 44         | >144         | ...                 | 1400           |
| 6th microjet| 09:32:39        | 917.5,89.2          | 3.5 ± 0.34  | 0.5 ± 0.34 | ...             | 54 ± 18      | ...                 | 1400           |

Notes.

* The coordinates of the bottom of these jets as seen in IRIS 1400 Å.

* The errors are estimated from the instrumental resolution.

* The speed of the large jet is obtained from the S–T map of IRIS SJ 1400 Å, and that of a microjet is estimated by their lengths divided by the time it reaches the top.

* In which passbands the jet was clearly seen; EUV: the AIA EUV passbands; 1400: the IRIS 1400 Å passband.
compact bright thread wrapped by blurred surroundings (see the animation associated with Figure 1). We can see that it contains both bright and dark components in AIA 171 Å and 94 Å passbands (Figures 1(c) and (d) for example). The dark component of the jet shows up as a bright structure in the AIA 304 Å image while it is dark in the AIA channels with higher representative temperatures (see Figure 1). While we also found the jet is associated with the eruption of a twisted transition region loop (see Section 3.3), the dark component of the large jet is made of plasma that belonged to the transition region. Based on the response temperatures of the AIA passbands (O’Dwyer et al. 2010), this jet should have a multithermal nature including plasma with temperatures from the transition region to the corona. Based on the SJ 1400 Å images, its length is measured as 29″ and the width of its compact bright component is about 1″/5. The dark component best seen in the AIA 171 Å channel has a width of about 2″/5.

The large jet possesses both upward motion in the early stage (as seen in all EUV passbands of AIA and IRIS SJI) and downward motion in the later stage (in all AIA EUV channels except 94 Å). In Figure 2, we show the spacetime (S–T) maps obtained along the large jet as seen in IRIS SJ 1400 Å and AIA 171 Å and 94 Å passbands. Based on these S–T maps, we found that the upward motions have a velocity of ~175 km s⁻¹ in SJ 1400 Å, ~116 km s⁻¹ in AIA 171 Å, and ~94 km s⁻¹ in AIA 94 Å, and the downward motions seen in AIA 171 Å have a velocity of ~49 km s⁻¹ (see Figure 2).

The spectrograph slit is perpendicular to the trajectory of the jet (see Figure 1(a)), which is about 15″ away from the footpoint. It allows us to study the evolution of the spectra of a cross section of the jet. In Figure 3, we show the evolution of the slit images of the spectral windows of Si IV 1403 Å, C II 1336 Å, and Mg II k 2796 Å. We can see that most spectra show clear enhanced wings. The extensions of the enhanced wings of the spectra are different from one location to another, demonstrating that the jet should consist of multiple fine threads.

Focusing on the Si IV spectra, one can see that non-Gaussian profiles are common. While the jet is moving upward, we observe spectral profiles with enhanced wings at their red ends as far as at Doppler shifts of 150 km s⁻¹ (see Figure 3(a1)), again indicating the highly dynamic nature of the jet. After that, the Doppler shifts of the enhanced red wings become smaller (see Figure 3(b1)). At 09:43:11 UT, about 5 minutes after the beginning of the jet, the ejected materials start falling back, enhancements can be seen at both red and blue wings (Figure 3(c1)). At 09:46:26 UT, only blue-wing enhancements are seen (Figure 3(d1)). Such behaviors of the spectral profiles are consistent with the dynamics of the jet as seen by the IRIS and AIA imagers. Such non-Gaussian profiles with strong emission in the line center and extensive enhanced wings are typical of the so-called “explosive events” (e.g., Dere et al. 1989; Innes et al. 1997; Huang et al. 2014, 2017), which are thought to be signatures of magnetic reconnections via plasmoid instability (Innes et al. 2015). We believe that these spectra in the present case are not due to reconnection because the location where the spectra are obtained is far away from the energetic sites. After carefully checking, we found that there exists a brightening in the background before arrival of the jet (Figure 4(a)), and thus we believe that the strong emissions in the line cores are mostly from the background and the extended wings are due to the jet.

With the IRIS spectral data of the O IV line pair at 1399.8 and 1401.2 Å and the CHIANTI atomic database (Dere et al. 1997, 2019), we are also able to derive the electron density of the jet. When the jet passes through the field of view of the slit (Figures 4(b)–(d)), we produce the spectral profiles averaged over the cross section of the jet and shown in Figures 4(e)–(g). The profile obtained at 09:39:09 UT (at the stage of moving upward) is obviously non-Gaussian and can be fitted by a double Gaussian model (Figure 4(e)). Because of the dynamics

![Figure 2](image-url) Spacetime plots along the trajectory of the EUV jet (see the green diamond symbols in Figure 1(a)) taken from IRIS SJ 1400 Å images (a), AIA 171 Å (b), and AIA 94 Å (c). The apparent speeds derived from these plots are also marked.
of the jet, we believe the emissions at the wings are contributed by the jet. With the line ratio using only the Gaussian components at the wings, the electron density is found to be $1.5 \times 10^{11}$ cm$^{-3}$. The mean profiles obtained at 09:43:11 UT (about at the fallback) and 09:46:07 UT (at the stage of falling back) are single Gaussian as shown in Figures 4(f) and 4(g). The electron densities derived for those two line pairs are found to be $4.4 \times 10^{10}$ cm$^{-3}$ and $4.9 \times 10^{10}$ cm$^{-3}$, respectively. The decrease of electron density is possible due to material falling back. These values suggest that transition region materials have been ejected from the footpoint.

3.2. Six Transition Region Microjets

In Figure 5, we show the SJ 1400 Å and AIA 1600 Å images and the HMI magnetogram of the region around the footpoint of the large jet. Six microjets are associated with a set of dynamic bright dots (BDs) found in the north of the dome-like structure (see Figure 5(a)). These BDs and microjets are clearly seen in IRIS SJ 1400 Å and AIA 1600 Å, but invisible in all AIA EUV channels (see Figures 1 and 5). Therefore, we believe they are transition region structures. These BDs are associated with microloop-like features (hereafter, microloops) in the transition region, which will be described in detail later. Please note that these microloops mostly are very small and can be better followed in the associated animations. The speed of a microjet is estimated as its length divided by the time it takes to reach its top.

Although the region is close to the limb and the magnetogram is blurred, it can still give a rough picture of the magnetic environment of the events. The HMI magnetogram (Figure 5(c)) shows complex mixed polarities in the region. Together with the locations of these BDs, their
associated microloops and microjets and the dome-like structure, we identify a set of polarities that are crucial in the eruption of the sequence of events (see Figure 5(c)). In these polarities, N1, N2, N3, P1, P2, and P3 are associated with the BDs and microloops; N4 links to an “open field” that is determined from the locations of the microjets, and N5 and the surrounding positive polarities (marked as P5 and P6) are associated with the dome-like structure.

In Figure 6, we show the IRIS SJ 1400 Å running difference images obtained at the time when the microjets are best seen. Their dynamic evolution is easier to follow in the associated animation. These microjets are very small in size, with less than 1” in width and a few arcseconds in length. The footpoints of these microjets are changing back and forth in the south–north direction that will be described in detail later. To investigate the evolution of the footpoints of these microjets and the associated microloops, we show IRIS SJ 1400 Å images of the region in
Figure 7 and the associated animation. Please note that the microjets are hardly seen in these images because the scaling has been adjusted to show microloops in their footpoints. The details of the evolution of these microjets are given below.

The first microjet is first seen at 09:17:17 UT, and lasts for about 90 s (denoted by the arrows in Figure 6(a)). Its width and length are about 0\(^{\circ}\)7 and 4\(^{\circ}\)6, respectively. Its speed is estimated to be about 47 km s\(^{-1}\). In Figures 7(a1)–(a5) and the associated animation, we show the evolution of the footpoint region of this microjet. We observe a transition region microloop in the footpoint that changes its connection simultaneously when the microjet is occurring. Before occurrence of the microjet, a microloop connects the polarities of P3 and N2 (see the dashed lines in purple in Figures 7(a1)–(a2)). After the microjet, we see a new microloop connecting the polarities of P3 and N4 (see the dashed lines in cyan in Figures 7(a3)–(a4)), which then disappears (see the associated animation). The new microloop is smaller than the preexisting one apparently. Considering the location of the microjet (see the yellow line in Figure 7(a3)), we believe that this microjet results from the reconnection between the microloop and an ambient open field.

The second microjet starts at about 09:19:08 UT (denoted by the arrows in Figure 6(b)). It can only be seen in three frames of the series of SJ 1400 Å images, and thus should have a lifetime less than 54 s. It has about 0\(^{\circ}\)8 width and about 3\(^{\circ}\)3 length. Its speed is estimated to be 59 km s\(^{-1}\). It has a typical inverted-Y shape that is better seen in the animation. The connection of microloops in its footpoint changes from P1 and N1 before the occurrence of the microjet to P1 and N2 afterwards (see Figures 7(b1)–(b5)).

The third microjet starts at about 09:22:39 UT, and lasts for about 90 s (denoted by the arrows in Figure 6(c)). It has about 0\(^{\circ}\)7 width and 6\(^{\circ}\)3 length. Its speed is estimated to be about 50 km s\(^{-1}\). Before occurrence of this microjet, we find that a microloop that connects the polarities of P2 and N2 moves toward northwest (see Figures 7(c1)–(c3)). While the microjet is clearly seen, a new microloop connecting the south footpoint of the previous microloop and that of the jet is formed (see Figures 7(c4)–(c5)). The newly formed microloop connects the polarities of P2 and N1, and it seems to be larger than the preexisting one.

The fourth microjet starts at about 09:26:39 UT, and lasts for about 90 s (marked by the arrow in Figure 6(d)). It has about 0\(^{\circ}\)6 width and 8\(^{\circ}\)0 length. Its speed is estimated to be about 64 km s\(^{-1}\). Before the occurrence of this microjet, we observe that a brightening with a semicircle shape appears in the footpoint, and we suggest it is a newly emerged microloop. While this brightening is growing, the microjet takes place at its north footpoint. A microloop much smaller than the previous one is found in the footpoint of the microjet.

Figure 6. Running difference images taken at the time when the microjets (denoted by green arrows that point to the bottom, middle, and top parts of a jet) are clearly seen. An associated animation is given online. The animation includes the evolution of this field of view from 09:17:17 UT to 09:48:55 UT. The real-time duration of the animation is 14 s. (An animation of this figure is available.)
The fifth microjet starts at about 09:30:15 UT, and lasts for about 144 s (see the arrows in Figure 6(e)). It has 0''6 width and 3''0 length. Its speed is estimated to be about 67 km s$^{-1}$.

Before the occurrence of this microjet, we observe a rising microloop that connects the polarities of P3 and N3 (Figures 7(e1)–(e4)). The microjet apparently sets out from the top of the microloop during its expansion. The size of
microloops found after the microjet does not change much from before.

The sixth microjet starts at about 09:32:39 UT, and lasts for about 54 s (see Figure 6(f)). It seems to be the consequence of the fifth microjet and its speed cannot be estimated. We see the fifth microjet swings in the southeast direction. It then attaches to an elongated feature that extends almost in parallel to the fifth microjet, and produces the sixth microjet (see Figures 7(f1)–(f5)). This microjet has about 0'5 width and 3'5 length.

After eruptions of these microjets, at the north to the dome-like feature we observed twisted loops start untwisting and rising. The rising of these twisted loops seem to trigger the large jet and lighten the dome-like structure. Since these twisted loops can only be seen in the IRIS SJ 1400 Å passband, here we called them “transition region flux ropes.” Please note that we cannot confirm whether they are actually typical flux ropes because of the resolution of the instrument. In the next section, we will describe in detail the evolution of the transition region flux ropes and the process that triggers the large jet from the dome-like structure.

3.3. Transition Region Flux Ropes and Triggers of the Large Jet

The transition region flux ropes first appear in IRIS SJ 1400 Å images at about 09:32:10 UT. They extend toward southwest and connect a location near the footpoint of the fifth microjet and the south of the dome-like structure (see Figure 8 and the associated animation). In the flux ropes, at least two bright threads can be identified in the SJ 1400 Å image (see the dashed lines marked in Figure 8). In Figures 8(b)–(j), we outline the geometries of the two bright threads of the flux ropes when they are evolving. By following their evolution, we can see untwisting and rising motions of these bright threads (better seen in the animation associated with Figure 8).

The triggering processes of the large jet can be seen in Figure 9. At about 09:38:03 UT, almost at the same time the large jet takes place, the dome-like structure is lightened up (see Figure 9(g)). At the top of the dome, a compact brightening appears slightly before the brightening of the dome-like structure (see the cross symbols in Figures 9(g)–(h)), and that might be the magnetic reconnection point (or null point) of the large jet. The brightenings in different fans of the dome-like structure appear successively. The size of the base of the dome is about 8' in diameter (see Figures 9(g)–(l)).

4. Discussion

Based on the observations, in Figure 10 we give a cartoon diagram to illustrate how the large jet may be triggered and what roles the series of TR microjets may play. Before start of the sequence of events, the possible magnetic geometry is given in Figure 10(a) where the polarities found in Figure 5 are also denoted. Please notice that a polarity marked here is not infinitesimal, and field lines rooted in the same polarity as shown in the cartoon are not necessarily connecting the same point. The BDs seen in the IRIS SJ 1400 Å are associated with the loops shown on the left; the dome-like structure is shown in gold on the right; and the TR flux ropes are shown in brown and connect the system of BDs and the dome-like structure. The TR flux ropes are suppressed by a loop system associated with the polarities of “N2,” “N3,” “P2,” and “P3,” and possibly by the dome. We assume the microjets flow along “open” field lines and thus their initial locations provide tracers to the locations of “open” field lines (blue lines in Figure 10).

The speeds of the microjets are relatively large in the transition region (compared to the sound speed and Alfvén speed in general). We suggest these microjets are results of magnetic reconnection between the microloops and “open” field lines. Taking into account the variation in the locations of these microjets and their concomitant dynamic microloops, we further discuss the physical processes of these events in what follows.

The sequence of the events starts from the first microjet, which results from magnetic reconnection between the microloop that connects “N2” and “P3” (pink line in Figure 10(a)) and the nearby open field (blue line in Figure 10(a) rooted in the polarity of “N4”). This step removes the first shell that constrains the TR flux ropes. After this reconnection, the root of the “open” field changes to “N2,” and
the newly formed microloop connecting “N4” and “P3” might submerge eventually.

The second microjet takes place due to reconnection between the microloop connecting the polarities of “N1” and “P1” (purple line in Figure 10(b)) and the “open” field rooted in “N2.” This step allows the “open” field to shift to “N1” and the newly formed microloop to connect “N2” and “P1.” This newly formed microloop sinks below the solar surface. It allows the microloop connecting the polarities of “N2” and “P2” to rise (see the cyan line in Figure 10(c) and Figure 10(d)). This then triggers the third microjet and allows the “open” field to shift back to “N2” (see Figure 10(e)). The reconnection resulting in the third microjet actually generates a larger loop as demonstrated in the observations. Please notice that Figure 10(d) needs to be thought in 3D, and the reconnection is a typical component reconnection rather than an antiparallel one.

The fourth microjet appears to be the result of reconnection between the “open” field and newly emerging loops (see the gray line in Figure 10(f)). In this process, the root of the “open” field shifts to “N3,” close to the loop system that constrains the TR flux ropes (Figure 10(g)).

The fifth microjet could be result of another component reconnection between the “open” field and the microloop (see Figure 10(g). Although such reconnection might not change the general geometry of the magnetic field much, the footprint of the close loop switches to the location where the “open” field previously was, and that removes the last constraint on the TR flux ropes (see Figure 10(h)).

The TR flux ropes that have lost constraints might undergo untwisting and rising. This can push the “open” field toward the dome and then cause occurrence of the sixth microjet. The rising TR flux ropes can also push the fans in the dome upward. The sixth microjet can also provide additional disturbance to the dome-like structure. Under this circumstance, the large jet is triggered. Both fans in the dome and the TR flux ropes can reconnect with the open fields of the dome (Figure 10(i)). That generates the large jet, and it naturally contains both cool (in the TR flux ropes) and hot (heated in the reconnection) plasma. At this stage, the eruption of the large jet follows the procedures, the same as the minifilament scenario (e.g., Sterling et al. 2015; Wyper et al. 2017).

Although the proposed scenario well explains the observations, the current data do not include precise observations of the magnetic field that are key to verifying any of these magnetic geometries. This would require observations from a line of sight perpendicular to this region. While these microjets might only be resolved from a side view, multiple satellites equipped with both magnetic and multiwavelength imagers with high spatio-temporal resolution are essential to provide solid evidences for the scenario. Such data might be achieved with multiple missions, such as a combination of the Solar Orbiter (Müller et al. 2020) and IRIS. Future missions with multiperspective satellites, like the Solar Ring Mission (Wang et al. 2020), if equipped with high-resolution EUV and magnetic imagers, will also help. On the other hand, we cannot rule out the possibility that the TR flux ropes are not preexisting but formed during the occurrence of the series of TR microjets.
5. Conclusions

In the present paper, we report on IRIS and SDO observations of a sequences of jets in the solar atmosphere. It consists of a large EUV jet and a series of transition region microjets prior to that. We have conducted a detailed analysis of their physical properties and small-scale dynamics in their footpoints, including small-scale TR loops and flux ropes and a dome-like structure. We found that the transition region microjets might play a crucial role in the eruption of the large jet. Based on the observations, we propose a scenario to illustrate how the series of transition region microjets facilitate the large jet.

The large jet originates from a dome-like structure and shows an inverted-Y geometry. It includes both cool and hot components, with temperatures from that of the transition region to the coronal. It has about 29″ in length, about 4″ in width, and about 10 minutes of lifetime. Its upward speed is higher than 170 km s\(^{-1}\) as derived from the IRIS SJ 1400 Å spacetime map, while its falling speed is much smaller (∼50 km s\(^{-1}\)). Using the O IV line pair of 1399.8 Å and 1401.2 Å, the electron density of the large jet is found to be about \(1.5 \times 10^{11}\) cm\(^{-3}\).

The series of microjets are visible only in the high-resolution data from the IRIS SJ 1400 Å passband, suggesting they are likely to be transition region phenomena. They have sizes of <10″ in length and <1″ in width. Their lifetimes are about 1–2 minutes and their speeds are in the range of 50–70 km s\(^{-1}\). We find that these TR microjets are associated with dynamics of microloops (with length less than 10″) in the transition region. Occurrence of a microjet is always accompanied by a change of geometry of microloops in its footpoint, and the location of the following microjet also changes accordingly.

We find that a bundle of TR flux ropes connects the region of the microjets and the dome-like structure in the base of the large jet. Following the microjets, the TR flux ropes undergo untwisting and rising motions and lead to an eruption of the large jet and also lightening of the dome-like structure. Our study is consistent with previous ones in that mini-filament eruption is the mechanism for a coronal jet, and further suggests that such a “mini-filament” could be a transition region structure.

Based on the observations, we propose a scenario involving a series of magnetic reconnection processes to explain the sequence of the events in the following steps: (1) the TR flux ropes were constrained by microloops at the beginning; (2) the constraints of the TR flux ropes are removed by magnetic reconnections that also generate the TR microjets; (3) the TR flux ropes lose constraints and become unstable; (4) the untwisting TR flux ropes interact with the dome, release their cool plasma into the spine of the dome, and result in the large jet.

Our observations demonstrate that the mass and energy couplings between the corona and lower atmosphere are complex. To understand this complex process, small-scale dynamics in the lower solar atmosphere are crucial. Although many of them might not carry directly mass and energy to the corona, they could be important for creating suitable magnetic
and plasma environments that promote energetic events linking the solar corona and the lower atmosphere.

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