Bidirectional Reconnection Outflows in an Active Region

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Abstract

We report on bidirectional coronal reconnection outflows reaching $\pm 200 \text{ km s}^{-1}$ as observed in an active region with the Si IV and C II spectra of the *Interface Region Imaging Spectrograph* (IRIS). The evolution of the active region with an emerging flux, a failed filament eruption, and a jet is followed in *Solar Dynamical Observatory* (SDO)/Atmospheric Imaging Assembly (AIA) filters from 304 to 94 Å, IRIS slit jaw images, and SDO/Heliographic and Magnetic Imager movies. The bidirectional outflow reconnection is located at a bright point visible in multiwavelength AIA filters above an arch filament system. This suggests that the reconnection occurs between rising loops above the emergence of magnetic bipoles and the longer, twisted magnetic field lines remnant of the failed filament eruption one hour before. The reconnection occurs continuously in the corona between quasi-parallel magnetic field lines, which is possible in a 3D configuration. The reconnection also triggers a jet with transverse velocities around 60 km s^{-1} . Blueshifts and redshifts along its axis confirm the existence of a twist along the jet, which could have been transferred from the filament flux rope. The jet finally blows up the material of the filament before coming back during the second phase. In the H α Dopplergrams provided by the MSDP spectrograph, we see more redshift than blueshift, indicating the return of the jet and filament plasma.

Key words: radiation: dynamics – Sun: activity – Sun: UV radiation – techniques: imaging spectroscopy

Supporting material: animations

1. Introduction

1.1. History

Solar jets are collimated ejections of plasma through the corona. They are transient events. In the 1970s, cool ejections had already been observed in H α and were called surges (Roy 1973). They were observed in the Ca II K line (Shimizu 2009), Ca II 8542 Å line (Robustini et al. 2018), and C IV line (Schmieder et al. 1983, 1987) with the UVSP (Woodgate et al. 1980) on board the *Solar Maximum Mission* (SMM). In these papers, the jets are described as fan-shaped or comb-shaped. Roy (1973) reported a strong initial acceleration with peak velocities of 150 km s^{-1} and extensions up to 50 Mm. Deceleration due to gravity eventually caused these surges to reverse direction and fall back toward the solar surface. A good correlation was found between the H α and C IV radial velocities ($40\text{--}60 \text{ km s}^{-1}$; Schmieder et al. 1983). Even in high-resolution observations (Asai et al. 2001; Yang et al. 2016; Reid et al. 2018; Robustini et al. 2018), the velocities of cool dense surges are not so extreme as those in Roy's paper. Note that 40 km s^{-1} is a standard value. Besides, the H α data seem to indicate the presence of a shock wave in the chromosphere, at the top of surges (Schmieder et al. 1983). Microturbulence of 130 km s^{-1} for the C IV line was found and interpreted to be unresolved velocity structures (Schmieder et al. 1983). Surges were frequently associated with Type III bursts (Mein & Avignon 1985; Chiuderi-Drago et al. 1986), implying that the cool material followed open field lines. In Schmieder et al. (1988), the kinetic and potential energies of the surge were at least two orders of magnitude higher (10^{28} erg) than the equivalent radiative energy loss in the X-ray

(HXIS on SMM). With the *Yohkoh* soft X-ray telescope, the fine structure of the X-ray jets with their reversed Y shape were well observed (Shimojo et al. 1996). Multiwavelength coronal observations showed that cool and hot transient ejections can coexist (Schmieder et al. 1995; Canfield et al. 1996; Chae et al. 1999; Shen et al. 2017). With the X-ray telescope on board *Hinode* (XRT), jet fine structures have been studied at a resolution of arcseconds and a cadence of minutes (Cirtain et al. 2007). Now, with SDO/Atmospheric Imaging Assembly (AIA), jet fine structures are observed in all temperatures. Many studies concern the speed of the jets and their recurrent behavior (Nisticò et al. 2009; Su et al. 2012; Guo et al. 2013; Schmieder et al. 2013; Zhang & Ji 2014; Chen et al. 2015; Yang et al. 2015, 2011; Chandra et al. 2017; Joshi et al. 2017a, 2017b; Huang et al. 2017; Bai et al. 2019).

1.2. Jet Trigger Models

Triggers of plasma jets have been extensively studied in theoretical models. Magnetic reconnection between emerging flux and open field lines looks to be the popular answer to explain standard jets (Heyvaerts & Priest 1983; Shibata et al. 1992, 2007; Moreno-Insertis & Galsgaard 2013; Schmieder et al. 2014; Raouafi et al. 2016; Wyper & DeVore 2016; Tian et al. 2018b; Nóbrega-Siverio et al. 2017). Recently, the term “blow jet” was introduced, referring to when a jet is triggered by the eruption of a mini filament and the whole region blows up. Ni et al. (2017) explained that coronal jets are due to plasmoid formation caused by Kelvin–Helmholtz instabilities. Another possible way of triggering jets is through the presence or injection of magnetic helicity (Pariat et al. 2009, 2010, 2015). The jets related to the light bridge in sunspots are very

Table 1
List of Observations of *IRIS* and MSDP on 2017 March 30

Instrument	Time Sequence UT	Raster Characteristics	Lines	Temperature K	SJI Characteristics
<i>IRIS</i>	09:07–12:35	Pointing:	226", 347"		
		Field of view (FOV):	30" $\times$ 119"		FOV: 120" $\times$ 119"
		Steps:	16 $\times$ 2"	Mg II k: 2796.4 Å	2796 Å
		Step Cadence:	9.2 s	Mg II h: 2803.5 Å	2832 Å
		Spatial Resolution:	0".16635	C II: 1334 Å, 1335 Å	1400 Å
				Si IV: 1402 Å, 1393 Å	1330 Å
MSDP	09:05–13:25	FOV:	435" $\times$ 269".5	H α :	6563 Å
		Time Resolution:	30 s		8000 K
		Pixel Size:	0".5		

particular due to the coupling of convective motions and the magnetic field. Waves are the principal promoter of such jets (Tian et al. 2014, 2018a; Hou et al. 2017). For standard jets, it is frequent to see twist flows along jets in AIA movies (Toriumi et al. 2015). Recent Dopplershifts measured in the Si IV line with the *Interface Region Imaging Spectrograph* (*IRIS*; De Pontieu et al. 2014) reveal helical motion along jets (Cheung et al. 2015) and could be the signature of the existence of magnetic helicity leading to jets. For the case of emerging flux, the majority of observations suggest that non-potential magnetic flux is emerging close to jets (Török et al. 2009) and that brightenings, miniflares, or UV bursts are frequently observed at the base of jets (Shibata et al. 2007; Uddin et al. 2012; Young et al. 2018).

1.3. Observations of Reconnection

Observational evidence for reconnection is largely indirect, resting on observations of variations in solar X-ray morphology and sudden changes in the magnetic topology. The apparent association between small-scale dynamic events, brightenings, and magnetic bipoles is interpreted as flux emergence. Only a few works have studied the reconnection sites, which, by definition, are smaller than the spatial resolution of the instruments. Dere et al. (1991) were the first to see explosive events in Si IV spectra with large extended wings using the rocket flight HRTS spectrograph. Innes et al. (1997) showed that non-Gaussian profiles using SUMER spectra could be interpreted as bidirectional jets ejected from reconnection sites above the solar surface. Yokoyama & Shibata (1996) and Archontis et al. (2005) proposed models of bidirectional flows in the reconnection of emerging flux with the environment. Recently, with *IRIS* spectra, Li et al. (2018), Tiwari et al. (2018), Tian et al. (2018b), and Chen et al. (2019) showed the existence of these bidirectional jets in the network. However, Curdt et al. (2012) suggested that these explosive events could be explained by rotational motions in narrow unresolved structures, which could correspond to spicule-sized jets with strong spinning motions. Interpreting the cause of such explosive events with the high-resolution observations of *IRIS* is an ongoing pursuit.

The motivation for producing this paper was initiated by observing tiny jets in the *IRIS* slit jaw images (SJIs) on 2017 March 30 during an international campaign between *IRIS*, *SOHO*/SUMER spectrograph, and ground-based instruments. The objective of the paper is to understand the trigger of these jets.

In Section 2, we present the instruments used for this work. In Section 3, we present the evolution of the activity within the region as a result of the emerging flux, e.g., failed filament eruption, bright point creation, and generation of a twisted jet. A potential scenario is proposed for triggering the plasma tiny jets with reconnection between potential state emerging loops and the twisted magnetic field lines of the remnant flux rope of the erupted filament. In Section 4, we focus on the *IRIS* spectra (Si IV and C II) of the bright point at the reconnection point, which exhibits bidirectional flows in very localized pixels (size of *IRIS* pixel = 0".167). The reconnection with the emerging flux occurs successively with individual overlying magnetic field lines in the corona as the emergence continues for a duration of 10 minutes.

2. Instruments

2.1. Solar Dynamics Observatory

On board the *Solar Dynamics Observatory* (*SDO*), the AIA (Lemen et al. 2012) provides multiwavelength imaging data, and the *Helioseismic and Magnetic Imager* (HMI; Schou et al. 2012) provides continuum intensity data. The AIA data at various passbands are as follows: 304 Å (He II, $T \sim 0.05$ MK), 171 Å (Fe IX, $T \sim 0.6$ MK), and 131 Å, 211 Å, 94 Å (Fe XVIII, $T \sim 6.3$ MK). In the other passbands, the data are not as clear, so we restrict our study to these filters. The AIA data cadence in these channels is 12 s. The pixel size is 0".6 pixel resolution. The processed disambiguated HMI vector magnetic field data are obtained with a 12 minute cadence and a 0".5 pixel resolution, provided by the HMI team (Scherrer et al. 2012).

2.2. IRIS

The *IRIS* field of view was focused on the AR NOAA 12644. The pointing of the telescope was 226", 347" with a field of view of 120" $\times$ 119" for the SJIs. The characteristics of the observations are presented in Table 1. We use the SJI 1330, 1400, 2796 Å data for this study. The SJI 1400 Å filter emission includes the total emission of the Si IV 1402 Å and 1393 Å lines within a range of about 40 Å formed in the transition region ($T = 80,000$ K), the SJI 1330 Å emission includes the C II line formed at $T = 30,000$ K, and the SJI 2796 Å emission mainly comes from the Mg II k line. The Mg II h and k lines are formed at chromospheric temperatures, e.g., between 8000 and 15,000 K (De Pontieu et al. 2014; Alissandrakis et al. 2018). The coalignment between the different optical channels of *IRIS* was achieved by using the

Figure 1. Eruption of the filament F1 and activation of the filament F2 in the active region NOAA AR12644 on 2017 March 30 observed with AIA filter 304 Å. HMI magnetic field contours are overlaid on the AIA maps in the top panels (blue/yellow contours indicate positive/negative polarities). In the bottom left panel, a bright region under F1 indicates an emerging flux.

derot solar software to correct the differential rotation. SJI in the broadband filters (1330, 1400, 2796 Å) were taken at a cadence of 37 s.

IRIS performed a 16-step coarse raster observation from 09:07 UT to 12:35 UT on 2017 March 30. The raster step size is 2'', so each spectral raster spans a field of view of 32'' × 119''. The nominal spatial resolution is 0''.16635. The details are presented in Table 1. Calibrated level 2 data are used in this study. Dark current subtraction, flat-field correction, and geometrical correction have been taken into account in the level 2 data (De Pontieu et al. 2014).

We use the spectra in the Mg II (2796.4, 2803.5 Å), Si IV (1393.8, 1402.8 Å), and C II (1334.5, 1335.7 Å) lines. The cadence of a slit crossing the same location is 148 s (2 minutes 28 s). During the observing time, 84 raster images have been reconstructed in these six wavelengths. We analyze in this paper the 11 rasters corresponding to the rising time of the jet.

2.3. Multichannel Subtractive Double Pass Spectrograph (Meudon Solar Tower)

We also follow the evolution of the jet in H α provided by the Multichannel Subtractive Double Pass spectrograph (MSDP) operating at the Meudon solar tower.

The Meudon MSDP observations of NOAA 12644 in H α consist of a series of five spectral images with 10'' overlaps in each time sequence, which allow us to obtain a field of view of 435'' × 269''. Sequences of observations are done during 30 minutes or 15 minutes with a 30 s cadence. The obtained data have been processed with the MSDP software (Mein 1991). On 2017 March 30, ten sequences of observations were obtained between 09:05:24 UT and 13:25:47 UT (Table 1). The exposure time was 50 ms for the first six sequences and 80 ms for the subsequent four sequences. In each MSDP pixel, an H α line profile is obtained over a wavelength range of ± 0.7 Å. Background subtractions are used to reduce scattering effects on line profiles.

Figure 2. Active region NOAA AR12644 on 2017 March 30 observed with AIA 171 Å during the eruption of F1 (top left panel), and HMI longitudinal magnetic field (right top panel). The AIA image is overlaid with the HMI magnetic field contours. The small box is the field of view of *IRIS* SJI (Figures 4 and 7). The large box is the field of view of the NLFFF extrapolation (Figure 3). The blue circle indicates the emerging magnetic polarities. Bottom panels: H α observations of F1, F2, and the jet from the MSDP. Animations of the AIA and HMI figures are available in the animated Figures 5 and 4, respectively.

3. Environment of the Event

3.1. Pre-jet Phase/Flaring Filament

The active region NOAA 12644 (AR) was located N12W21 at 19:30 UT on 2017 March 30 close to the disk center. The AR magnetic field consists of a leading negative magnetic polarity and a following positive magnetic polarity. The polarity inversion line (PIL) has a boomerang shape with one arm east–west oriented southward of the active region and the second arm oriented northeast/southwest northward of the active region. At 07:52:05 UT, two filaments F1 and F2 are observed with the AIA filter at 304 Å (the black structure in Figure 1). F2 lies between relatively strong fields along the southern part of the PIL, and F1 lies between weaker magnetic fields along the northern part of the PIL. The presence of these two filaments and the direction of the PIL indicate that there is a strong shear in the middle of the AR. Between 08:00 UT and 09:06 UT, the two filaments undergo strong disturbances. F2 becomes bright with flows along the spine, and F1 erupts partially with material flowing up and down along long twisted

loops (see Figure 5’s animation of the AIA 304 images). The filaments are well observed in the AIA 304 filter and in H α after the eruption (Figures 1 and 2, bottom panels).

A nonlinear force-free field (NLFFF) extrapolation of the magnetic field via the Wiegelman method (Wiegelman 2004; Wiegelman et al. 2006) has been performed using an HMI magnetogram obtained prior to the eruption of the filament. The two main polarities of the region are linked by potential magnetic field lines (yellow lines in Figure 3). In the central part of the region, one can see highly sheared/twisted field lines at the location of the filament F1 during different phases of the failed eruption (blue and red lines in Figure 3).

3.2. Emerging Flux

The temporal evolution of the longitudinal magnetic field observed with HMI exhibits a region of flux emergence (EMF) located close to the elbow of the boomerang-shaped PIL (between 05:00 UT and 10:00 UT, see Figure 4’s animation of the HMI images). This EMF is located below the right leg of

Figure 3. Nonlinear force-free field extrapolation of the magnetic field vector of HMI of the active region NOAA12644 at 07:48 before the filament eruption. The yellow lines represent large-scale loops in a potential field, and the twisted field lines could represent the remnant magnetic field lines supporting the filament F1 at rest and during the eruption. The white square is the field of view of Figure 4.

F1 (blue circle in Figure 2, top right panel). Figure 4 shows the evolution of the EMF in the HMI magnetograms between 05:42 UT and 09:55 UT in a field of view corresponding to the *IRIS* SJI. Initially, the positive polarity P0 (see labels on bottom right panel in Figure 4) exists. This polarity does not evolve much except for its magnitude, which increases. Meanwhile, a new bipolar distribution of magnetic field (P1, N1) emerges southward of P0 with multiple flux cancellations between them.

This flux emergence is associated with brightenings observed at 304 and 171 Å in AIA filters (Figure 1 bottom panels), between 08:30 UT and 08:50 UT, which have the shape of magnetic loops connecting P1 and N1 (hereafter the Arch Filament system—AFS). Brightenings in the AFS are again seen around 09:55:29 UT at the time of the peak in intensity (Figure 5). A few minutes after, a new loop system appears in 171 Å and connects N1 and P0. These loops seem to become higher and higher above the AFS with time in the AIA 304 Å (see Figure 5, right panels) and in the AIA 171 Å filter (Figure 2, right bottom panel). Their footpoints are distant from 15'' to 20'' (10.4–14.4 Mm). The AFS appears before the N1–P0 loops, and the latter form above the AFS and are pushed up as the AFS grows.

The *IRIS* observations start at 09:07 UT after the filament eruption and cover the emerging flux region. *IRIS* SJIs have a better spatial resolution than that of AIA, with their spatial nominal resolution of 0''16635. We select a small field of view (65'' × 65'') in the field of view of the 1400 Å SJIs, focusing on the emerging flux (Figure 7). The emerging flux is well developed between 09:55:50 UT until 10:18:30 UT over P1, N1, and P0 (see the black circle in Figure 7, bottom panel). At 09:55:50 UT, we see EMF between P1 and N1. Later, at 10:15:34 UT, we identify arcades or loops joining N1 and P0. They are tangent to the jet, confirming what is observed in the AIA 304 Å movie but with a better spatial resolution.

This strongly suggests that the flux emergence is pushing up the loops, which destabilizes the overlying loop system. This

EMF could be responsible for the filament destabilization and the formation of the jet. The cancellation could also be the trigger of the jet, as is commonly the case (Young et al. 2018).

3.3. UV Burst

In the AIA movies, we observe a short-duration bright point, a UV burst, and the development of a jet. The UV burst (A) is visible at 10:07 UT in all of the AIA filters: 304, 171, 211, 131, and 94 Å (left panels in Figures 5 and 6) and in the *IRIS* 1400 Å SJIs (Figure 7), indicating a temperature $>10^5$ K. The appearance of this UV bright burst suggests the release of energy ensured by the magnetic reconnection process. However, the UV burst observed at the base of the jet is not visible in cool lines (Mg II lines), as is the case for canceling flux and reconnection in the low atmosphere. This provides a good argument for coronal reconnection (see Section 4.1).

IRIS 1400 Å SJIs cover the emerging flux region and the low part of the extended jet (Figure 7). The brightest point in the close vicinity of A is already detected at 10:02:57 UT (middle left panel) and moves northeast between 09:55 UT and 10:08 UT. It is also very visible in the AIA movies. Its displacement can be quantified in the *IRIS* SJIs as follows: at 09:55:50 UT, there is a bright point at $x = 240''$, $y = 342''$. At 10:02:07 UT, just above it, we see an elbow at $x = 238''$, $y = 351''$. At 10:05:42 UT, the elbow is situated at $x = 238''$, $y = 355''$. At 10:08:47 UT, it is in B at $x = 238''$, $y = 358''$, and we see the extension of the jet.

The site of reconnection around A moves by about 15'', rising with a velocity of 15 km s^{-1} progressively while the AFS and loops are rising. Reconnection occurs between the rising loops and the long preexisting loops for 10–15 minutes. The slit of *IRIS* crosses exactly the core of the UV burst, bright point in A, during this time. The *IRIS* spectra in Si IV and C II exhibit strong emission in both wings, suggesting the existence of bidirectional flows. This is what we call “the bidirectional reconnection outflows” (see Section 4.2). Before analyzing the *IRIS* spectra, we focus on the development of the jet using AIA and *IRIS* SJIs.

3.4. Jet Extension

In the AIA movies (in the animation of Figure 5), after 10:02:21 UT, we observe a jetlike event starting from the UV burst and propagating along long preexisting loops, which could correspond to the twisted field lines of the filament F1 (Figures 5 and 6). It ends at 10:24 UT, according to the AIA movies. The jet is visible in all of the AIA channels, indicating that the plasma of the jet is hot.

In *IRIS* 1400 Å SJIs (Figure 7), the onset of the jet is identified by bright loops with an elbow at 10:02:37 UT and 10:05:42 UT, similar to the loops visible in AIA 304 Å at 10:07 UT (Figure 5). The jet is developing in the northeast direction in the first phase until 10:15 UT and then in the southwest direction in the second phase (Figure 7). During phase 1, the jet consists of material moving along thin individual loops. During phase 2, between 10:13 UT and 10:18 UT, the jet is developing with many fine structures. These fine structures consist of different threads that are not parallel; a few of them make angles reaching 10° – 20° , which could correspond to some twist. The emission along each thread is not uniform but presents some patchy enhancements of $10''$ in length. The global section width of the jet reaches $10''$

Figure 4. Evolution of the magnetic field before the filament eruption on 2017 March 30, showing the emerging bipoles (enclosed by a blue circle in the bottom right panel). The emerging flux consists of three small polarities: P0, P1, and N1. An animation of the HMI6173 images is available. The animation runs from 5:40 to 10:40 UT, and the images are not annotated.

(An animation of this figure is available.)

(7500 km). With a time–distance analysis, we determine an upward velocity of the jet of about 67 km s^{-1} between 09:57 UT and 10:46 UT in 1330 Å SJs including C II line (Figure 8). We use a large slit between the two blue lines to take into account the shift of the jet toward the east.

Additional spectral information is provided by the MSDP instrument operating at the Meudon solar tower in the $H\alpha$ line. The MSDP observations start after the filament eruption F1.

We focus our study on the sequence between 10:03 UT and 10:28 UT covering the time interval of the jet observations. At 10:07 UT, there is no bright point corresponding to the UV burst and no dark region corresponding to the plasma jet. It is certainly because the ejected plasma is hotter than 10^4 K . At 10:21:03 UT, the filament F1 is reformed with two components, and a cool jet is observed as a dark elongated area, like a filament (Figure 2 bottom panels).

Figure 5. Reconnection in A (bright point) and expansion of the jet at 10:07 UT and 10:21 UT observed in 304 and in 171 Å with AIA filters. The black box is the field of view of *IRIS* SJIs shown in Figure 7. An animation of the 304 and 171 Å images is available. The animation runs from 9:30 to 10:40 UT, and the images are not annotated.

(An animation of this figure is available.)

We conclude that the jet is a hot jet ($T > 10^5$ K) during the first phase of its development and a cool jet during the second phase ($T > 10^4$ K).

4. Evidence of Reconnection Outflows

4.1. Possible Scenario for the Reconnection

Figure 9 displays a simplified sketch that shows the initial magnetic configuration and its evolution during the observed jet. In panel (a), the green, red, and yellow field lines belong to the rising loops above the AFS, while the light blue, purple, and black field lines could belong to remnant twisted field lines of the filament F1. The growing green field line pushes these latter field lines, leading to the formation of the elbow shape as seen in the left columns of Figures 5 and 7 (see also the animation). Due to the presence of the elbow, we could conclude this shows field lines with a bald patch in the low atmosphere and reconnection above the canceling flux, like in the Ellerman bombs (EBs). However, we note that the UV

burst is not really visible in the chromospheric lines but, on the contrary, in the hot channels of AIA. We are in favor of reconnection in the corona above the loops (green, red, and yellow), seen with an apex at 10 Mm high. When these loops interact with the preexisting loops (light blue, purple, and black), we expect a current sheet to form and magnetic reconnection to occur. This is consistent with the observation of the jetlike event. In panels (a) and (b), we see that the green and light blue field lines have exchanged their connectivity. The green field line, which is closed in (a), becomes open in (b), while the light blue field line, which was open, becomes closed. Then, the red field line reaches and reconnects with the purple field lines (Figures 9(c) and (d)), and finally, the yellow field line reconnects with the black field line (Figures 9(e) and (f)). We propose that the jetlike event we observed follows the scenario described in Figure 9 and that the UV burst observed in the AIA filter images and in the *IRIS* SJIs occurs in the location where magnetic reconnection takes place between the large-scale twisted field lines with untwisted small-scale closed

Figure 6. Reconnection in A (bright point) and expansion of the jets at 10:07 UT and 10:21 UT observed in 211, 131, and 94 Å with the AIA filters. An animation of the 211, 131, and 94 Å AIA images is available. The animation runs from 9:30 to 10:40 UT, and the images are not annotated.

(An animation of this figure is available.)

loops above the AFS. We note that the emerging flux and the P0–N1 loops in the middle of the active region give a configuration with quasi-parallel curved arcades. This configuration is very particular, and reconnection is not possible in two dimensions (Yokoyama & Shibata 1996). However, it is possible in a 3D configuration (Démoulin et al. 1996 in Figures 2(e) and (g)). This was confirmed by 3D simulations (Galsgaard et al. 2007), and several observational studies show such situations (Dalmasse et al. 2015; Joshi et al. 2019).

Besides, the emerging flux in the present study seems to be in a potential state with no shear or twist. We do not see any rotation of pores. The reconnection occurs with the twisted field lines supporting the failed eruption filament. After reconnection, the jet follows untwisting field lines. We suggest that there is a transfer of twist between the twisted remnant field lines of the filament and the jet.

The above description of the event aims to set up the scene for the high-resolution spectral analysis of the UV burst with a

Figure 7. Jet observations in the AR NOAA 12644 between 09:55:50 UT and 10:18:39 UT in *IRIS* SJIs in the 1400 Å passband. The blue circle encloses the emerging flux identified by the letters P0, P1, and N1 (Figure 4). “A” indicates the elbow of a loop above the reconnection site. The field of view is indicated in Figure 5. An animation of the *IRIS* 1400 Å SJIs is available. The animation runs from 9:08 to 10:40 UT, and the images are not annotated.

(An animation of this figure is available.)

bidirectional reconnection outflow indicated by the double arrow in Figure 9.

The analysis of the spectra of *IRIS* in UV lines and of the MSDP in $H\alpha$ allows us to further explore our scenario. It confirms the existence of twist along the jet and provides evidence of the reconnection site with bidirectional outflows. It is the first time that such a reconnection site has been observed in the corona.

4.2. Bidirectional Reconnection Outflows

The *IRIS* spectra were recorded in four UV lines during the onset of bidirectional reconnection outflows. Figure 10 shows two examples of rasters of Si IV spectra (left panels) and the reconstructed images (right panels) using the integrated intensity of the Si IV line extracted from the *IRIS* spectra. In the spectra, we identify a bidirectional emission enhancement in slit 13 (top left panel) and large extensions in individual

Figure 8. SJIs in 1330 Å overlaid by the 16 slits used in the coarse raster. The slit for the distance–time diagram is drawn in white. Right panel: the distance/time plot for the jet between the two blue lines shown in the left image. The speed of the jet is around 67 km s^{-1} .

Figure 9. Sketch of the jet with recurrent reconnections between P0–N1 loops above the P1–N1 emerging magnetic flux (EMF) and overlying magnetic field lines. Green/red/yellow magnetic field lines reconnect sequentially with blue/purple/black magnetic field lines. The jet follows the reconnected lines: green in (b), red in (d), and yellow in (f). The reconnection point with bidirectional reconnection outflows is indicated by a double arrow. The blue, purple, and black field lines are the twisted filament magnetic field lines. The vertical dashed line in each panel indicates the direction of the rising small loops.

pixels, either in the blue wing (slit 7 in the bottom left panel) or in the red wing at the edge or top of the jet (slit 10 in the bottom left panel). The weak emission in the wing of Si IV spectra at the top of the jet equivalent to 100 km s^{-1} suggests the existence of shocks when meeting the overlying magnetic

loops, as has already been observed at the top of surges (Schmieder et al. 1983).

During the reconnection phase of the emerging flux with the overlying magnetic field, the *IRIS* slit scans the region of reconnection between 09:55 UT and 10:08 UT included by

Figure 10. Left panels: *IRIS* rasters with 16 spectra in the Si IV 1402.77 Å line through the region showed in Figure 8. Top left panel: raster 4 obtained between 10:04:37 and 10:06:56 UT during phase 1 of the jet. Slit 13 (10:06:28 UT) at $y = 354''$ shows the bidirectional reconnection outflows. Bottom left panel: raster 8 obtained between 10:16:57 and 10:19:16 UT during phase 2 of the jet. Redshift is around $y = 360''$ and blueshift in $y = 370''$. Right panels: reconstruction of *IRIS* raster images from the Si IV spectra. Slits cross the jet between $y = 360''$ and $400''$. The bright point in slit 12 at $y = 320''$ is at the edge of the EMF.

Table 2

Description of the *IRIS* Spectra in Si IV 1393.78 Å *IRIS* Rasters with the Bidirectional Reconnection Outflows and Twisted Motions in the Jet with Blueshifts and Redshifts

N	Time (slit 1) UT	Time (slit 16) UT	Comments on the Dopplershifts (the numbers are coordinates in arcseconds)
1	09:57:13	10:02:00	reconnection starts to be visible in slit 14
2	10:02:09	10:04:28	reconnection at 10:04:00 UT in slit 13 ($x = 235$)
3	10:04:37	10:06:56	reconnection at 10:06:28 UT ($x = 235$, $y = 354$)
4	10:07:05	10:09:34	reconnection at 10:08:56 UT
5	10:09:33	10:10:52	red/blueshift parallel to the axis of the jet
6	10:12:01	10:14:20	strong blueshift around ($x = 235$ – 240 , $y = 350$)
7	10:14:29	10:16:48	idem
8	10:16:52	10:19:16	idem+blue/redshift parallel to the axis of the jet
9	10:19:25	10:21:44	blueshift in $y = 370$ and redshift around $y = 360$
10	10:21:53	10:24:12	blueshift around $y = 370$ – 375 redshift in $y = 360$
11	10:24:21	10:26:40	blueshift in $y = 390$ and redshift below redshift and blueshift parallel areas

Figure 11. Evolution of the spectra at the reconnection point in C II (1335.7 Å) from $t_1 = 10:01:32$ to $t_{10} = 10:23:44$ UT in slit 13 from raster 1 to raster 10. The line Si IV is centered on 1393.7551 Å. The Δt between two spectra is 148 s. The y-range shows the solar-y coordinate on the left and the pixel coordinate on the right.

chance in the small field of view of the rasters ($32'' \times 120''$). The UV burst (bright point A) is crossed in slit 14 at 09:55 UT and later in slit 13 (Table 2). In the first four rasters, the Si IV and C II line profiles exhibit strong emission enhancements in both wings, which we qualify as bidirectional reconnection outflows (Figure 10, top left panel). The position of these wide Si IV and C II spectra is moving along slit 13 (see the C II spectra extracted from the first 10 rasters between 10:01:32 UT and 10:23:44 UT in Figure 11). This displacement corresponds to the displacement of the UV burst that we have observed in AIA and in *IRIS* SJI (UV burst A, UV burst B) for 10–15 minutes. The bidirectional emission enhancement spectra moves up by 10,000 km with a velocity of the order of 15 km s^{-1} . This shift toward higher altitudes could correspond to continuous reconnection with higher loops as we proposed in the sketch (see the double arrows in Figures 9(b), (d), and (f)).

The UV burst reveals blueshifts and redshifts of the order of $100\text{--}200 \text{ km s}^{-1}$ in neighboring pixels, indicating the spatially resolved bidirectional reconnection outflows. The redshift and blueshift pixels are at a distant of less than $1''$. Si IV and C II line profiles of neighboring pixels in Figure 12 exhibit three components: a main component at rest and two lateral components that correspond to 200 and -150 km s^{-1} . The rest component with high intensity would be due to the heating of the plasma at the reconnection site. The Mg II line profiles do not show any emission enhancement or broadening in the wings (Figure 12, lower panels). Figure 13 shows the spectra obtained simultaneously in the four lines observed with *IRIS* at the reconnection point in slit 13 and confirms that the bidirectional jet is nearly not visible in the Mg II lines. It means that the reconnection site plasma is hotter than 20,000 K, which is the temperature of the ionization of Mg II. This explains why we do not see a bright point in H α and why it is seen in all of the filters of AIA until 94 Å ($T = 6.3 \text{ MK}$).

The bidirectional reconnection outflows look similar at a first glance to recent observations of UV bursts observed in the chromosphere with *IRIS* (Peter et al. 2014; Grubecka et al. 2016; Zhao et al. 2017; Tian et al. 2018b; Young et al. 2018; Chen et al. 2019). In those cases, the blueshifts and redshifts are observed in UV bursts in Si IV and also in the Mg II lines. The UV bursts correspond to canceling flux during emerging magnetic flux and to low-altitude reconnection sites

(chromosphere). They are commonly called EBs and IRIS bomb (IB) bursts. In our case, there is no signature in the cool lines (H α and Mg II lines) and no corresponding canceling flux.

On the contrary, the reconnection site is in the corona. The UV burst occurs at a high altitude estimated to be 10,000 km at the top of the loops, which have distant footpoints of approximately 20,000 km. The reconnection occurs at high temperatures, as we have observed with AIA 94 Å. Therefore, we are expecting that the speed of the reconnection reaches the Alfvén speed (around 1000 km s^{-1}). According to the proposed scenario that we illustrate in the sketch of Figure 9, we are tentatively able to explain why these high velocities are not reached. It is due mainly to the magnetic configuration of the two interacting magnetic systems. The possible scenario of the magnetic configuration of the region suggests that the UV burst corresponds to the reconnection site between the emerging flux continuously rising and the overlying twisted magnetic field remnant of the failed filament eruption. This continuous rise explains the shift toward the higher altitude noted in the bidirectional reconnection jet. In our scenario, the reconnection occurs between nearly parallel magnetic field lines. Let us assume that locally the 2.5D geometry is valid. In this case, the magnetic field component $B_{\parallel}$ along the main direction of the field B should be dominant and relatively passive. The reconnection should only involve weaker vector field components $B_{\perp}$ perpendicular to the main field direction. This implies that the speed reconnection jets should be of the order of the so-called perpendicular Alfvén speed $c_{\perp}^{\perp} = B_{\perp}/\mu\rho$, which ought to be smaller than the full Alfvén speed $c_A = B/\mu\rho$. This naturally explains the relatively low velocities of the bidirectional jet, which does not reach the Alfvén speed of the corona. This argument could justify our designation of the bidirectional flow as a reconnection.

The existence of the bidirectional outflows could also be interpreted as due to the spinning of the jet, producing a twisted and untwisted structure, as Curdt et al. (2012) and Pariat et al. (2015) suggested. The fact that we see the bidirectional outflow only in one slit is a strong argument against this solution, however. In the present study, we believe that our scenario justifies that the UV burst with the bidirectional flows corresponds to a bidirectional flow reconnection event.

4.3. Dopplershifts of the Jet

We analyze the 11 rasters reconstructed from the *IRIS* spectra and corresponding to the rise time of the plasma jet between 10:04 to 10:26 UT in Si IV (1402.8 Å) and in C II (1334.5 Å). The reconstructed images have a low spatial resolution in the x coordinate because of the $2''$ step between the two slits (Figure 14). In these images, we identify the main features that were described previously in Figure 7, e.g., the elbow of the magnetic field lines, the bright unresolved region around A (UV burst), and the jet. By comparing the spectra and the reconstructed image, we are able to identify the spectra of individual pixels, e.g., the large spectra of the pixels in the bright region A in slit 13 that we analyzed in the previous section. In the same reconstructed image, we distinguish the faint plasma jet and some blueshifts and redshifts in the spectra (slits 1–12) at the corresponding location. Comments on the Dopplershifts visible in the spectra with their coordinates are enumerated in Table 2.

To have a global view of the velocities inside the jet, we fit the profiles of Si IV (1393.8 Å) and Si IV (1402.77 Å) lines

Figure 12. Profiles of the C II, Si IV, Mg II (1394), and Mg II (1403) lines are plotted for 11 selected pixels along slit 13, three times each, corresponding to the second through fourth rasters at 10:04:00, 10:06:28, and 10:08:56 UT (from the left to right columns). The x-axis in each panel is in units of LOS velocity. The green, red, and black profiles are, respectively, for pixels $y = 418, 417, 411$ and $y = 432, 430, 425$ in columns 1 and 2. The red and black profiles correspond to pixels $y = 448, 436$ in column 3.

Figure 13. Bidirectional reconnection outflows in the *IRIS* spectra of the C II, Si IV (1394 Å), Si IV (1403 Å), and Mg II lines for slit 13 around 10:06 UT during the third raster. The line Si IV is centered on 1393.7551 Å. The y-range in each panel shows the solar-y coordinate on the left and the pixel coordinate on the right. The green, red, and black arrows in the second panel mark the pixels' spatial locations from column 2 of Figure 12.

Figure 14. *IRIS* rasters (from raster 2 to raster 10). Each raster is obtained with 16 spectra in Si IV 1393.76 Å line in 2 minutes 28 s. White arrows follow the jet rise. The elbow and the reconnection point are indicated by black arrows.

with a Gaussian profile. This assumption is reasonable for the majority of the pixels, but it is a rough assumption for profiles presenting double peaks, which indicate clearly the presence of two structures along the line of sight with different velocities. Dopplergrams have been reconstructed for the 11 considered rasters. The four panels of Figure 15 show the evolution of the LOS velocity. The two top panels present the observations during phase 1 with blueshift and redshift patterns, and the bottom panels present the observations during phase 2 with mainly strong redshifts.

The velocity value is limited to $\pm 10 \text{ km s}^{-1}$ but higher Dopplershift values exist up to $\pm 70 \text{ km s}^{-1}$ at the reconnection site. The velocity values are in fact underestimated values due to the single Gaussian assumption. Between 10:04 UT and 10:16 UT (phase 1), we see blueshifts and redshifts next to each other parallel to the jet axis. This could be interpreted as a twisted and untwisted jet as it becomes wider. The LOS

velocities in these strands can reach ± 20 to 30 km s^{-1} . Between 10:16 UT and 10:26 UT (phase 2), the jet material is propelled up with a velocity of 70 km s^{-1} , similarly to the transverse velocity measured with the intensity. At the bottom, redshifts are observed (Figure 15).

These blueshift and redshift areas could also belong to different parallel structures, as is suggested in the high spatial resolution of the *IRIS* SJI (see Figure 15, top left panel).

While the blueshift area is moving toward the north, an extended redshift area is growing in space toward the south. Redshifted material seems to go toward the solar surface.

Figure 15 shows examples of the Dopplershifts measured in the H α line with the MSDP superposed on the intensity. The two components of F1 seem to be reformed at 10:17 UT. The onset of the jet is not visible in H α . Only phase 2 of the jet is detected in H α with mainly downflows. The jet top is outside of the field of view. The Dopplershift maximum is around

Figure 15. Jet observations. Top panels: on the left, intensity from SJIs in 1330 Å, and the related Dopplershift raster map using the raster spectra in Si IV (1402.8 Å) covering the SJI time (rasters 3, 4). The vertical dashed lines limit the raster field of view. The yellow lines underline individual loops in the top panels. Bottom panels: H α Dopplershift map (blue and red) combined with H α intensity (yellow and green) and the related Dopplershift raster map in Si IV (1402.8 Å) covering the SJI time (rasters 9, 10). Contours of the redshift area indicate the jet and dashed lines filament F1. The white rectangle in the bottom panels is the field of view of the *IRIS* raster. The dashed square represents the field of view of the SJIs in Figure 8.

5 km s^{-1} . The H α profiles are very broad profiles, suggesting strong velocity gradients and/or high microturbulence. Such broad profiles have already been observed for surges (Schmieder et al. 1983; Mein & Avignon 1985). In the Dopplershift maps, we see mainly redshifts, indicating material coming back, from material of the erupting filament. After 10:17:03 UT, redshifts correspond to jet area. At 10:24:33 UT, the downflow area is wide and is followed in the south by a long and large dark path in the intensity until the redshift in the penumbra of the sunspot (Evershed effect). Between 10:17:03 UT and 10:24:33 UT, the blueshift and redshift seem to belong to two different structures: the blueshift should correspond to the filament, and the redshift to the jet. However, the red area is underlined by a blue line along its southern part. This could indicate some rotation of the jet structure or be due to the uncertainties in the computation of the Dopplershifts in such broad profiles where blueshift and redshift can be present. An analysis with cloud models could help to interpret such profiles.

We compare the Dopplergrams in the Si IV line with the Dopplergrams in H α (Figure 15). The jet is detected in H α only during the second phase of the jet after 10:17 UT. The jet shows the same behavior with red area at the bottom, and blue area at the top on the east side. According to the coalignment of the two fields of view, the blue/redshift areas belong more to different structures than to the same jet in rotation.

5. Conclusion

A jet occurred in the active region NOAA 12644 (N12, W21) on 2017 March 30. It lasted less than 30 minutes with two distinguishable phases. The jet developed at height with a transverse velocity of the order of 67 km s^{-1} along different paths. The different paths or structures are observed with the different AIA filters and the Si IV and C II slit jaws of *IRIS*. The jet is initiated by reconnection above an emerging magnetic flux with overlying magnetic field lines. In AIA images and *IRIS* SJIs, we see at the base of the jet a UV burst in the hot channels of AIA and in Si IV and C II SJIs. The small field of

view rasters of *IRIS* ($32 \times 120''$) cross the UV burst by chance for a duration of 10–15 minutes. The reconnection site is characterized by a bidirectional reconnection outflow located in the corona (10 Mm high) that exhibits LOS velocities reaching $\pm 200 \text{ km s}^{-1}$ measured in the C II and Si IV lines. The reconnection site is heated to temperatures of the order of 6 MK but is not visible in $H\alpha$ nor the Mg II lines. The reconnection occurs between coronal loops growing due to the emerging magnetic flux and forward long twisted loops, which could belong to the filament channel. The twist could have been transferred from the twisted filament support to the jet.

The Dopplershift maps obtained in the Si IV rasters with *IRIS* show redshift and blueshift next to each other along the jet axis. These blueshift and redshift areas suggest twisted and untwisted structures of a flux rope as the jet progresses and expands. This structure occupies the same area in projection as the filament eruption. In the second phase, the jet is wide ($10''$ wide). While the material at the top is escaping with blueshifts, the bottom part exhibits redshifts. The downflow of the jet observed in Si IV is consistent with the $H\alpha$ downflows observed with the MSDP.

The cause of the jet is the consequence of reconnection between an emerging flux that is growing below long twisted loop remnants of an erupted filament. This leads to the interpretation of the bidirectional outflows as the reconnection jet (Figure 9). We observe, nearly for the first time in an active region, a bidirectional reconnection outflow with a velocity up to $\pm 200 \text{ km s}^{-1}$. Further study should be done on the line profiles in Si IV to see if there are unresolved structures along the LOS with higher velocities. Presently, we explain the low values of the flows compared with the coronal Alfvén speed as due to the magnetic configuration of the two interacting systems (emerging flux and overlying field). This scenario presents a reconnection between nearly quasi-parallel magnetic field lines, and only the perpendicular components reconnect effectively. The weakness of the perpendicular components explains why the speed of the reconnection does not reach the Alfvén speed.

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