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Meng Ni   Liang Hongfei   Zhou Xinping

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Abstract

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Full Text

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Recurrent Bidirectional Jets Triggered by Magnetic Reconnection Between Adjacent Filaments*

Meng Ni[1] Liang Hongfei[1†] Zhou Xinping[2‡]

(1 School of Physics and Electronic Information, Yunnan Normal University, Kunming 650500)
(2 School of Physics and Electronic Engineering, Sichuan Normal University, Chengdu 610066)

Abstract Using high-temporal-resolution and high-spatial-resolution observational data from the Solar Dynamics Observatory (SDO), we conducted a detailed analysis of a group of recurrent bidirectional jet events occurring in the same source region. The results show that the generation of these jets is closely related to the interaction between two small-scale adjacent filaments and to the magnetic-reconnection process in the jet source region. Observations indicate that the adjacent ends of these two filaments were rooted in opposite magnetic polarities within the source region. As the filaments gradually approached each other, a distinct brightening patch appeared in their interaction region. Subsequently, a pair of high-temperature plasma jets moved in opposite directions along the two filamentary structures, exhibiting typical bidirectional-jet characteristics. The combined analysis shows that the observed bidirectional jet

events have evident recurrent properties, and that their formation mechanism is consistent with the recently proposed model of magnetic reconnection between adjacent filaments. This mechanism differs from the traditional scenario in which bidirectional jets are thought to be triggered mainly by magnetic reconnection between a newly emerging bipolar magnetic field and an overlying horizontal magnetic field.

Keywords Sun: jets, Sun: filaments, Sun: corona, magnetic reconnection, plasmas

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1 Introduction

Solar jets are a type of transient and collimated plasma flow. They were first discovered through observations in the Hα band in the 1940s, and at that time were called Hα surges. With the development of observing techniques, jets are no longer limited to the Hα band, but have also been widely observed in multiple wavebands such as the extreme ultraviolet (EUV) and X-rays. The spatial scales of solar jets vary over a wide range, from small nanometer-scale jets to large-scale jets that can extend over several solar radii. They usually occur between the chromosphere and the corona of the solar atmosphere[1-4]. Jet phenomena are widely distributed on the solar surface; they can appear not only in active regions[5-6] and quiet-Sun regions[7], but also in coronal holes.

With the continuous upgrading of observing instruments, solar jets have been detected by a variety of instruments in different wavebands. From the X-ray jets observed by the Soft X-ray Telescope (SXT) carried on the Yohkoh satellite[8-9], to the coronal jets observed in the EUV band in 1995 by the Solar and Heliospheric Observatory (SOHO)[3, 5, 10-13], multiwavelength observations of jets have gradually enriched people' s understanding of their physical properties. Based on these observations, researchers have obtained various key physical parameters of jets, all of which show relatively large ranges of variation. The heights of jets are about $1 \times 10^4 - 50 \times 10^4$ km, their widths are $1 \times 10^4 - 10 \times 10^4$ km, their speeds cover the range $10 - 1000$ km $\cdot$ s^{-1}, and their lifetimes range from several minutes to nearly 1 h[14-18].

The measurement of these parameters provides important observational evidence for a deeper understanding of the formation mechanisms and evolutionary processes of coronal jets. Solar jets are dynamical processes in which plasma is ejected in a beam-like form along magnetic field lines. These continuously upward-directed plasma ejections can provide mass and energy flux for the upper solar atmosphere, and may have effects on coronal heating and solar

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(2023NSFSC1351)
† lianghongfei@ynnu.edu.cn
‡ xpzhou@sicnu.edu.cn

make important contributions during the wind-acceleration process[^1][^19-^22]. Liu et al.[^23], based on Hα spectral-line observations, analyzed jet activities related to newly emerging magnetic flux regions, and pointed out that the emergence and disappearance of magnetic flux are important physical mechanisms that trigger jets. It is generally believed in the community that the formation of solar jets mainly originates from the magnetic-reconnection process between newly emerging magnetic flux and the surrounding background magnetic field.

At present, studies of solar jets have covered many aspects, including jet classification, dynamic characteristics, triggering mechanisms, and their roles in solar physical processes. According to differences in jet morphology, they can usually be divided into anemone jets and two-sided jets[^24-^26]. Among them, anemone jets generally exhibit an inverted "Y" -shaped structure and are so named because their morphology resembles a sea anemone. Such jets usually consist of a bright base and a spire, and often occur in emerging flux regions (Emerging Flux Region, EFR) or active regions (Active Region, AR) in coronal holes. The magnetic-field structure of such jets is manifested as magnetic-field lines connecting the bipolar magnetic field within the active region and the surrounding unipolar magnetic field, with magnetic loops distributed radially. In contrast, jets accompanying emerging flux regions or active regions in quiet regions mostly appear as two-sided loop-like structures. Yokoyama et al.[^24] proposed that the formation of jets originates from magnetic reconnection between a pre-existing coronal magnetic field and a newly emerging magnetic field: when the coronal magnetic field is approximately horizontal, two-sided jets are prone to form; whereas under a vertical or inclined magnetic-field background, anemone jets are more readily produced.

With increasing observations and analyses of two-sided jets, new triggering mechanisms for jets have also been proposed. Tian et al.[^25] used joint observational data from the New Vacuum Solar Telescope (NVST) and the Solar Dynamics Observatory (SDO) on 2014 April 16 to carry out a detailed study of two two-sided jet events. The results showed that these jets originated from the magnetic-reconnection process between neighboring dark fibrils. This formation mechanism differs significantly from the previously more generally accepted model—namely, that two-sided loop-like jets are produced by magnetic reconnection between newly emerging bipolar magnetic fields and overlying horizontal coronal loops[^24,^26].

Based on SDO multi-band observational data, this paper investigates recurrent two-sided jet events occurring in the same source region. The results show that the formation mechanism of this type of jet is consistent with the "magnetic reconnection between neighboring dark fibrils" model proposed by Tian et al.[^25]. Further analysis indicates that, when multiple neighboring dark-fibril structures exist in the source region and the system is in an unstable evolutionary phase, their mutual interaction is more favorable for triggering magnetic reconnection and thereby producing two-sided jets. This result provides new observational evidence for understanding the repeated triggering and energy-release processes of two-sided jets, and provides a reference for exploring the physical connections among solar eruptive activities at different scales. The structure of this paper is arranged as follows: Section 2 introduces the observational instruments used and data sources; Section 3 describes the analysis methods and main results; Section 4 summarizes and discusses the conclusions of the study.

2 Observations

On 2013 November 30, a group of two-sided jet events that repeatedly occurred in the same source region was observed in solar active region 11908. To analyze the evolutionary process of these jets, this paper uses extreme-ultraviolet (EUV) observational data from the Atmospheric Imaging Assembly (AIA) aboard the Solar Dynamics Observatory (SDO). Four EUV passbands of AIA were mainly used: 304 Å, 171 Å, 193 Å, and 131 Å. The spatial resolution of AIA is 0.6″, and the temporal resolution is 12 s. To study the evolution characteristics of the magnetic field in the jet source region, line-of-sight magnetograms from the Helioseismic and Magnetic Imager (HMI) aboard SDO were also used, with a temporal resolution of 45 s.

3 Observational Results

This paper studies two-sided jet events that repeatedly occurred in the same source region in solar active region 11908 on 2013 November 30. Figure 1 shows observational images of the jet source region before the occurrence of the jets. The article analyzes the magnetic-field structure of the jet source region, in which the footpoint locations of two dark fibrils are indicated by contours in green (positive polarity) and red (negative polarity), respectively (the contour levels are ($\pm$)4, ($\pm$)5, and ($\pm$)10). It can be seen that the western dark fibril is rooted in the positive-polarity region (as indicated by the arrow P1 in Figure 1(a)), whereas the eastern dark fibril is rooted in the negative-polarity region (as indicated by the arrow N1 in Figure 1(a)). The overall jet source region presents a bipolar magnetic-field structure composed of positive and negative polarities (as shown in Figure 1(a)). Other panels show the same spatial region and are used to compare the characteristics in different passbands.

Figure 2 shows the detailed evolutionary process of the first jet observed in three SDO/AIA passbands, 304 Å, 171 Å, and 131 Å. From left to right, the panels show the pre-eruption phase, the pre-eruptive stage (columns 2–3), the eruption onset, and the mid-eruption evolution. Observations show that, before the jet occurred, the dark fibrils in the source region consisted of two thin, thread-like structures that were separated from each other but spatially adjacent (see the black dashed lines in Figure 2(b1)). Combined with Figure 1, it can be seen

Fig. 1

Figure 1: Fig. 1

that the two dark fibrils are rooted in positive and negative magnetic-polarity regions, respectively.

At 21:38:43 UT, the neighboring dark fibrils gradually approached each other due to perturbations, and in their convergence region (black [[unclear: sentence continues on next page]]).

A pronounced brightening appeared in the region indicated by the colored rectangular box. This indicates that, when two filament threads rooted in opposite polarities approached each other, magnetic reconnection may have been triggered, leading to rapid heating and brightening in the local region. Subsequently, jets formed along the filament path toward both sides. At 21:40:31 UT, plasma ejected in the directions of T1 and T2 could be observed (see Fig. 2(a4)), showing typical bidirectional-ejection characteristics.

Fig. 1 An overview of the region prior to the jet occurrence. Panels (a)-(d) show images in the AIA 171 Å, 131 Å, 193 Å, and 304 Å channels, respectively, overlaid with contours of the line-of-sight magnetic field observed by SDO/HMI at 21:35:40 UT (Universal Time). The green and red contours represent the positive and negative polarities of the HMI line-of-sight magnetic field, respectively. In panel (a), arrows P1 and P2 indicate positive-polarity regions, while arrows N1 and N2 mark negative-polarity regions.

After the first jet eruption, three more morphologically similar bidirectional jet events occurred successively in this source region, at 22:05 UT, 22:28 UT, and 22:55 UT, respectively. Figure 3 shows the evolutionary process of the four jets (J1, J2, J3, and J4) that occurred continuously from 21:39 UT to 22:58 UT. All four jets originated from the same location and appeared as bidirectional structures ejected in opposite directions along the filament-intersection region, exhibiting typical bidirectional-jet characteristics.

Figure 3 presents AIA 304 Å images before and after the jet eruptions. From the positions indicated by the arrows in Fig. 3(a1), (a3), (a5), and (a7), it can be seen that, before the jets occurred, distinct localized brightenings appeared in the source region. This may be direct evidence of magnetic reconnection between filament threads. After the brightening appeared in the source region, plasma ejection in opposite directions along the filament-head direction could be observed (see Fig. 3(a2)). The dashed lines in Fig. 3(a4) schematically indicate the spatial morphology of the fine structures in the source region after the jet occurred.

To further investigate the dynamical characteristics of the observed recurrent bidirectional jets, time-distance diagrams were constructed in this work based on AIA 304 Å images. These slices were selected along the dashed-line positions shown in Fig. 2(a5), in order to trace the ejection paths of the plasma in the four jet events. As shown in Fig. 4, the plasma propagated in opposite directions, displaying typical bidirectional-motion characteristics.

[Figure 2 image: detailed evolution of the first jet in AIA 304 Å, 171 Å, and 131 Å channels, with panels a1-a5, b1-b5, and c1-c5.]

Fig. 2 The detailed evolution of the first jet. Panels (a1)-(a5), (b1)-(b5), and (c1)-(c5) show time-sequence images in the AIA 304 Å, 171 Å, and 131 Å channels, respectively. In panel (a4), T1 and T2 mark the two propagation directions of the jet, and the dashed line in panel (a5) indicates the slice position used to produce the time-distance plot in Figure 4. The black rectangular boxes in panels (a2), (b2), and (c2) outline the initial brightening region of the first jet.

[Figure 3 image: evolution of four recurrent bidirectional jets J1-J4 in AIA 304 Å images, panels a1-a8.]

Fig. 3 Evolution of the four jets. Panels (a1)-(a8) AIA 304 Å images showing the evolution of the recurrent bidirectional jets J1-J4. The white arrows in panels (a1), (a3), (a5), and (a7) indicate the pronounced brightenings that appear at the onset of each jet. The arrow in panel (a2) marks the ejection direction of the jet, while the dashed curve in panel (a4) outlines the filamentary structure after the second jet.

By linearly fitting the slopes along the jet fronts, the ejection velocities of the four jets along the eastern and western sides were estimated: for J1, approximately 26 km $\cdot s^{-1}$ and 40 km $\cdot s^{-1}$, respectively; for J2, 32 km $\cdot s^{-1}$ and 45 km $\cdot s^{-1}$; for J3, 37 km $\cdot s^{-1}$ and 47 km $\cdot s^{-1}$; and for J4, 34 km $\cdot s^{-1}$ and 62 km $\cdot s^{-1}$. The velocity range of the four jets is 26-62 km $\cdot s^{-1}$, which lies within the typical velocity range of solar coronal jets. Each jet

the duration of the event was about 3-5 min, and the total duration of the four jets was about 1.5 h.

Fig. 4 Time-distance diagrams derived from the AIA 304 Å images, showing the eruption process of the recurrent bidirectional jets. The trajectories of the plasma moving in opposite directions and their corresponding velocities are indicated in the figure.

Fig. 4 Time-distance diagrams derived from the AIA 304 Å images, showing the eruption process of the recurrent bidirectional jets. The trajectories of the plasma moving in opposite directions and their corresponding velocities are indicated in the figure.

4 Results and Discussion

Using the high-temporal- and high-spatial-resolution observations from SDO, this paper has examined in detail the generation and evolution of recurrent bidirectional jets caused by magnetic reconnection between adjacent dark threads.

The observational results show that four consecutive bidirectional jet events all originated from the same source region and were closely related to two adjacent dark threads. In the first jet, the eruption speeds of the plasma to the west and east were about 26 $\mathrm{km \cdot s^{-1}}$ and 40 $\mathrm{km \cdot s^{-1}}$, respectively; in the second jet, the speeds were about 32 $\mathrm{km \cdot s^{-1}}$ and 45 $\mathrm{km \cdot s^{-1}}$, respectively; in the third jet, the speeds were about 37 $\mathrm{km \cdot s^{-1}}$ and 47 $\mathrm{km \cdot s^{-1}}$, respectively; and in the fourth jet, the speeds were about 34 $\mathrm{km \cdot s^{-1}}$ and 62 $\mathrm{km \cdot s^{-1}}$, respectively. These speed ranges are consistent with previous observational results for jets.

From Fig. 2, the formation and evolutionary details of the jets can be clearly seen. Before the jets occurred, there were two dark threads that were close to each other but still separated (see the two dashed lines in Fig. 2(b1)). Combined with Fig. 1, it can be seen that the footpoints of these two dark threads were anchored in the positive- and negative-polarity magnetic-field regions, respectively. By 21:38 UT, the gap between the dark threads had disappeared; the two dark threads came into contact, and a distinct localized brightening appeared in the source region. Some high-temperature plasma was ejected from the self-brightening region and flowed in opposite directions along the paths of the dark threads, exhibiting typical bidirectional-jet characteristics [27–29]. Consistent with previous studies [25, 27–29], this phenomenon indicates that magnetic reconnection occurred between the dark threads. Because the dark threads were rooted in magnetic-field regions of different polarities, their mutual approach and contact provided the conditions for magnetic reconnection; the energy released by the reconnection heated the plasma and caused it to erupt in opposite directions along the threads, thereby forming bidirectional jets.

In this observation, a total of four recurrent bidirectional jet events were identified within the same source region. As shown in Fig. 3, all four jets originated from the same magnetic activity region and erupted in opposite directions along the dark-thread junction region. The first contact of adjacent dark threads formed the first pair of bidirectional jets; subsequently, new dark threads formed again and, after approaching and contacting each other once more, triggered subsequent jets. This process occurred repeatedly within the same magnetic structure and is consistent with existing observational results [25, 27, 30], further confirming that bidirectional jets tend to recur near the same neutral line. Taken together, the observational results suggest that the multiple bidirectional jet events studied in this paper are all closely related to the magnetic reconnection process between adjacent dark threads, and that their formation mechanism is consistent with the model proposed by Tian et al. [25].

Compared with flares or coronal mass ejections (CMEs), jet phenomena are less prominent, but with improvements in observational-instrument performance and the enrichment of observational methods, their importance in solar atmospheric dynamics has become increasingly evident, and they have become one of the research hotspots. At present, studies of bidirectional jets remain relatively limited, which is closely related to the difficulty of identifying them observationally. Yokoyama et al. [24] pointed out that bidirectional jets do not necessarily appear as typical jet forms, but may only appear as transient loop-like brightenings [31–32]. Zheng et al. [30] argued that bidirectional jets may be as common as anemone jets, and that their "rarity" mainly arises from the difficulty of effectively identifying them under low-resolution observing conditions. At present, there are only a small number of observational reports on bidirectional jets [11, 25, 27, 30]. Among them, Alexander et al. [11] first reported bidirectional jets using data from the Transition Region and Coronal Explorer (TRACE) and Yohkoh; Jiang et al. [27] analyzed recurrent bidirectional jets and considered them to originate from the magnetic reconnection process between a newly emerging bipolar magnetic field and the overlying coronal magnetic field; Zheng et al. [30], in 2018, proposed a case of bidirectional jets associated with erupting plasma and twisted overlying magnetic fields, and argued that the jets were triggered by magnetic reconnection between overlying horizontal field lines and a loop-like structure. The results of the present study support the "formation of bidirectional jets through magnetic reconnection between adjacent dark threads" model proposed by Tian et al. [25]. This differs from the traditional model for coronal jets: the traditional model holds that jets are triggered by magnetic reconnection between a newly emerging bipolar magnetic field and the overlying coronal background field, whereas the results of this study show that some bidirectional jets do not depend on the emergence of new magnetic flux, but are instead triggered by magnetic reconnection between adjacent dark threads. Jets in the traditional model mainly occur in newly emerging magnetic-flux regions, whereas the newly proposed model is more likely to occur in⋯

In the interaction process within an already existing magnetic structure, the jet event in this study did not show obvious new magnetic-flux emergence characteristics; instead, it manifested as the gradual approach of adjacent dark lanes accompanied by localized brightening, subsequently triggering a two-sided jet. This is more consistent with the scenario of the magnetic-reconnection model for adjacent dark lanes. This research result further broadens the understanding of the diversity of triggering mechanisms for two-sided jets and provides important observational evidence for subsequent systematic statistical analyses and numerical-simulation studies.

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Recurrent Two-Sided Loop Jets Triggered by Magnetic Reconnection between Adjacent Filament Threads

MENG Ni[1] LIANG Hong-fei[1] ZHOU Xin-ping[2]

(1 School of Physics and Electronic Information, Yunnan Normal University, Kunming 650500)
(2 School of Physics and Electronic Engineering, Sichuan Normal University, Chengdu 610066)

Abstract The observations from the Solar Dynamics Observatory (SDO), characterized by high temporal and spatial resolution, were used to perform a detailed analysis of a series of recurrent bidirectional jet events originating from the same source region. The results show that the jet was closely associated with the interaction between two small-scale, adjacent dark filaments and the magnetic reconnection occurring in the jet source region. The observations reveal that the neighboring ends of the two filaments were rooted in magnetic polarities of opposite signs within the source region. As the filaments gradually approached each other, a pronounced brightening patch appeared in their interaction region. Subsequently, a pair of hot plasma jets propagated in opposite directions along the two filamentary structures, exhibiting typical bidirectional jet characteristics. Combined analyses indicate that the formation mechanism of the observed bidirectional jet is consistent with the recently proposed model in which magnetic reconnection between adjacent filaments plays a key role. This mechanism differs from the traditional scenario, where bidirectional jets are mainly triggered by reconnection between an emerging dipole and the overlying horizontal magnetic field.

Key words Sun: jets, Sun: filaments, Sun: corona, magnetic reconnection, plasmas

Note: Figure translations are in progress. See original paper for figures.