

Onset mechanism of an inverted U-shaped solar filament eruption revealed by NVST, SDO, and STEREO-A observations[★]

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ABSTRACT

Context. Solar filaments, also called solar prominences when appearing on the solar limb, consist of dense, cool plasma suspended in the hot and tenuous corona. They are the main potential sources of solar storms.

Aims. To understand the onset mechanism of solar filaments, we investigated the eruption process of an inverted U-shaped solar filament and two precursory jet-like activities.

Methods. Using observations from the New Vacuum Solar Telescope (NVST), the Solar Dynamics Observatory (SDO), and the Solar Terrestrial Relations Observatory-Ahead (STEREO-A), we investigated the event from two distinct observational perspectives: on the solar disk using NVST and SDO, and on the solar limb using STEREO-A. We employed both a nonlinear force-free field model and a potential field model to reconstruct the coronal magnetic field with the aim to understand its magnetic properties.

Results. Two precursor jet-like activities were observed before the eruption, displaying an untwisted rotation. The second activity released an estimated twist of over two turns. During these two jet-like activities, Y-shaped brightenings, which are newly emerging magnetic flux accompanied by magnetic cancellation, and the formation of newly moving fibrils were identified. When these observational features are combined, it can be inferred that these two precursor jet-like activities released the magnetic field that constrained the filament and were caused by newly emerging magnetic flux. Before the filament eruption, it was observed that some moving flows had been ejected from the site as the onset of two jet-like activities, indicating the same physical process as in the two jet-like activities. Extrapolations revealed that the filament was below the height of the decay index of 1.0 and had a strong magnetic field (540 Gauss) and a high twist number (2.4 turns) before the eruption. An apparent rotational motion was observed during the filament eruption.

Conclusions. We deduce that the solar filament, exhibiting an inverted U-shape, is a significantly twisted flux rope. The eruption of the filament was initiated by the release of constraining magnetic fields through continuous magnetic reconnection. This reconnection process was caused by the emergence of new magnetic flux.

Key words. Sun: activity – Sun: filaments, prominences

1. Introduction

Solar filaments are some of the most fascinating structures on the Sun. They consist of cool and dense materials that are suspended in the hot and tenuous solar corona. The materials appear as dark elongated features on the solar disk. They are seen as bright cloud-like structures when observed at the solar limb, when they are also called solar prominences (e.g., Martin 1998; Mackay et al. 2010; Wang et al. 2022a). They often lie above the magnetic polarity inversion lines (PILs) that separate the positive and negative polarities of the photospheric magnetic field (Babcock & Babcock 1955; Martin 1998). According to their locations, they can be divided into three classes: active region filaments, intermediate filaments, and quiescent filaments. Magnetic fields play a key role in the stability, formation, and eruption of filaments in the corona (Mackay et al. 2010). The

eruption of filaments would yield solar storms (e.g., solar flares, global waves, and coronal mass ejections (CMEs)), which have a significant effect on the solar atmosphere and interplanetary space (e.g., Wang et al. 2020, 2022b; Zhou et al. 2021).

Understanding the filaments or prominences in the corona is the main subject of solar physics, including their formation, eruption, and magnetic structure (Martin 1998; Chen et al. 2020). A magnetic flux rope and magnetic dips have been often discovered in many observations of the filaments, which suggests that the filament materials are supported by the magnetic tension (Gilbert et al. 2001; Su et al. 2015). Photospheric flux cancellation and convergence are thought to be crucial for the formation of filament magnetic structures (e.g., Chae et al. 2001; Wang & Muglach 2007; Yang et al. 2016). It is widely accepted that the magnetic structures of filaments are generally formed through surface actions involving magnetic reconnection, rather than subsurface actions (van Ballegoijen & Martens 1989; Wang et al. 2017). Yan et al. (2015) suggested that

[★] Movies are available at <https://www.aanda.org>

sunspot rotations and shearing motions cause the formation of two homologous filaments. On the other hand, solar jets or some small-scale activity around the filament might be an efficient way to carry the materials for the filament (e.g., Wang et al. 2018, 2019; Li et al. 2023).

Based on numerous numerical simulations and observations, many candidate mechanisms have been proposed to explain how the solar filaments erupt, including reconnection-driven processes (e.g., breakout models Antiochos et al. 1999, tether-cutting models Moore et al. 2001, and flux emergence models Chen & Shibata 2000; Lin et al. 2001) and ideal magnetohydrodynamics (MHD) instabilities (e.g., kink instability Sakurai 1976; Hood & Priest 1979, torus instability Kliem & Török 2006, and catastrophic model Lin & Forbes 2000). In the first category, the initiation mechanism relies on magnetic reconnections that rearrange the magnetic field, leading to the destabilization of the system. Magnetic reconnection beneath or above the filaments plays a crucial role in triggering the eruption of the filament (Chen et al. 2018; Leake et al. 2022). Newly emerging magnetic flux can also be considered to be a trigger of the filament eruption (Feynman & Martin 1995; Yan et al. 2020a). On the other hand, in the processes of ideal magnetohydrodynamic instabilities, any further change of the instability-related parameter in the magnetic field, for instance, the magnetic twist, the decay index of the overlying field (Cheng et al. 2017), would trigger the eruption. By performing MHD simulations, it was found that a magnetic flux rope becomes kink unstable when the twist number reaches about 1.8 turns (Török et al. 2004; Fan 2005). While the decay index of the background magnetic field reaches about 1.5, the magnetic flux rope will undergo torus instability and erupt successfully (Kliem & Török 2006; Aulanier et al. 2010).

Numerous efforts have been devoted to unraveling the initiation of solar eruptions. Cheng et al. (2013, 2020) proposed that the torus instability serves as the initiator and might impel the primary acceleration of the eruption. Some researchers argued that the tether-cutting reconnection mechanism causes the slow-rise phase, while the main acceleration was attributed to torus instability (Woods et al. 2018; Chen et al. 2018; Cheng et al. 2023). Jing et al. (2021) suggested that both torus and kink instabilities were crucial for the initiation in their study case. Furthermore, Ishiguro & Kusano (2017) introduced a novel type of instability known as a double-arc instability (DAI), wherein a sigmoidal configuration created by a double-arc electric current system destabilizes without weakening the overlying magnetic fields. Some observations are thought to be triggered by this mechanism (Kang et al. 2019; Kim & Yurchyshyn 2022). Recently, Jiang et al. (2021) argued that magnetic reconnection driven by photospheric shearing motion is significant in the initiation of solar eruptions. Despite the fact that most observed events can be interpreted with one or more of these models, the onset mechanism of solar eruptions remains a subject of intense controversy.

To gain a deeper understanding of the onset mechanism of eruptions, particularly involving active region filaments, we investigate an eruption of an inverted U-shaped solar filament in active region NOAA 12680 in this paper. By using stereoscopic and high-resolution observations, we study the initialization of the filament eruption and analyze two overlying precursor activities before the eruption. Furthermore, we also discuss and probe the onset mechanism of the filament eruption. The sections of this paper are organized as follows: observations and data are described in Sect. 2, the main analysis results are presented in Sect. 3, and the summary and discussions are given in Sect. 4.

2. Data analysis and methods

2.1. Data analysis

In this study, the data set is obtained primarily from the New Vacuum Solar Telescope¹ (NVST; Liu et al. 2014; Yan et al. 2020b), the Solar Dynamics Observatory² (SDO; Pesnell et al. 2012), and the Solar Terrestrial Relations Observatory-Ahead³ (STEREO-A; Kaiser et al. 2008). The NVST is a vacuum solar telescope with a 985 mm clear aperture located at Fuxian Lake, in Yunnan Province, China. It can provide high-resolution images of the $H\alpha$ band with a cadence of 11 s and has a CCD plate scale of $0''.165 \text{ pixel}^{-1}$. The $H\alpha$ images are recorded by a tunable Lyot filter with a bandwidth of $0.25 \text{ \AA}$, and the field of view (FOV) is about $150'' \times 150''$. The $H\alpha$ images were reconstructed by using the speckle-masking method (Xiang et al. 2016). All NVST $H\alpha$ images were normalized by the quiet Sun and aligned with each other based on a cross-correlation algorithm (Yang et al. 2015). The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012; Hoeksema et al. 2014) on board the SDO provided full-disk, multiwavelength, high spatio-temporal resolution imaging and magnetic data for this study. The extreme ultraviolet (EUV) images of 304, 171, and 193 Å from SDO/AIA were used to show information from the high chromosphere to the corona. They have a cadence of 12 s and a spatial resolution of $1''.2$. The line-of-sight (LOS) magnetic fields and vector magnetograms from the SDO/HMI were employed to show the magnetic information on the photosphere. Their spatial resolutions are $1''.0$, and their cadences are 24 s and 12 min, respectively. The AIA images were derotated to a reference time of 07:30 UT to remove the effect of the Sun's rotation and differential rotation, while the NVST $H\alpha$ images were carefully coaligned with SDO/AIA 304 Å images by matching specific features observed simultaneously. 195 Å EUV images from the Extreme Ultraviolet Imager (EUVI; Wuelser et al. 2004) on board the STEREO-A were used to show the event in the direction of angle 128° with the Sun-Earth direction. Their cadences and spatial resolutions are 2.5 min and $3''.2$, respectively.

2.2. Methods

To understand the magnetic properties associated with the filament eruption, we reconstructed the coronal magnetic field by a nonlinear force-free field (NLFFF) model based on the observed photospheric magnetic field. The NLFFF extrapolation was performed by using the weighted optimization method (Wheatland et al. 2000; Wiegmann 2004; Wiegmann et al. 2012) with the vector magnetograms observed by SDO/HMI. Before the extrapolation, we rebinned the boundary data by 2×2 to $0.72 \text{ mm pixel}^{-1}$. In this study, the extrapolation region lies within a box of $318 \times 266 \times 266$ uniform grid points, which corresponds to about $231 \times 193 \times 193 \text{ mm}^3$. The region can cover the full active region of interest, which is needed for the NLFFF model (De Rosa et al. 2009). Although there are some limitations of force-free magnetic field extrapolations when the effects of the plasma β are neglected (the ratio of the gas pressure to the magnetic pressure) that might contradict the actual situation in the corona, the NLFFF extrapolation might capture the magnetic structure and connectivity of the coronal magnetic field (Peter et al. 2015). Based on the three-dimension simulation data

¹ <http://fso.ynao.ac.cn>

² <https://sdo.gsfc.nasa.gov>

³ <https://stereo.gsfc.nasa.gov>

of the outer solar atmosphere by using the MHD Bifrost model (Carlsson et al. 2016), Fleishman et al. (2017, 2019) evaluated the nonlinear force-free field (NLFFF) reconstructions with different methods and different boundary conditions. They found that extrapolations from a force-free chromospheric boundary produce measurably better results than those from a photospheric boundary and that any chromospheric magnetic field data can measurably improve the reconstruction of the coronal magnetic field. In recent observations, reliable chromospheric magnetic fields are still hard to capture. In addition, the measurements of the photospheric magnetic field contain inconsistencies and noise, particularly in the transverse components. Therefore, it is acceptable that a preprocessing procedure is used for the SDO/HMI photospheric vector magnetograms to drive the observed nonforce-free data toward suitable boundary conditions for a force-free extrapolation (Wiegelmann et al. 2006). The input parameters μ_1 , μ_2 , μ_3 , and μ_4 were used in the default set as [1, 1, 0.001, and 0.01] for the preprocessing procedure. To assess how force free the photospheric boundary input is, the force (ϵ_{force}) and torque (ϵ_{torque}) balance parameters were calculated, which are defined by the following equations, respectively (Wiegelmann et al. 2006):

$$\epsilon_{\text{force}} = \frac{|\int_S B_x B_y dx dy| + |\int_S B_y B_z dx dy|}{\int_S (B_x^2 + B_y^2 + B_z^2) dx dy} + \frac{|\int_S (B_x^2 + B_y^2) - B_z^2 dx dy|}{\int_S (B_x^2 + B_y^2 + B_z^2) dx dy}, \quad (1)$$

and

$$\epsilon_{\text{torque}} = \frac{|\int_S x((B_x^2 + B_y^2) - B_z^2) dx dy|}{\int_S \sqrt{x^2 + y^2} (B_x^2 + B_y^2 + B_z^2) dx dy} + \frac{|\int_S y((B_x^2 + B_y^2) - B_z^2) dx dy|}{\int_S \sqrt{x^2 + y^2} (B_x^2 + B_y^2 + B_z^2) dx dy} + \frac{|\int_S y B_x B_z - x B_y B_z dx dy|}{\int_S \sqrt{x^2 + y^2} (B_x^2 + B_y^2 + B_z^2) dx dy}, \quad (2)$$

where B_x , B_y , and B_z are the three components of the vector magnetic field. (x, y) is the position of the magnetic field. A vector magnetogram is consistent with the force-free assumption when $\epsilon_{\text{force}} \ll 1$, $\epsilon_{\text{torque}} \ll 1$. The ϵ_{force} and ϵ_{torque} of the photospheric boundary were estimated to be about 0.3–0.4 before preprocessing. After preprocessing, the ϵ_{force} and ϵ_{torque} decrease sharply to about 10^{-4} and 10^{-3} , which means that the photospheric boundaries we input for the NLFFF extrapolation after preprocessing are consistent with the force-free condition.

Otherwise, the current-weighted average of the angles $\langle \theta_i \rangle$ is smaller than 10° , while the $\langle |f_i| \rangle$ are lower than 4×10^{-4} . Thus, the extrapolated magnetic fields satisfied both the force-free and divergence-free conditions (Wheatland et al. 2000).

Based on the extrapolated magnetic fields of NLFFF models, the twist number (T_w) was calculated by the equation (Berger & Prior 2006)

$$T_w = \int_L \frac{\mu_0 J_{\parallel}}{4\pi B} dl = \frac{1}{4\pi} \int_L \alpha dl, \quad (3)$$

where μ_0 , $J_{\parallel}$, B , α , and l are the magnetic permeability of the vacuum, the electric current component parallel to the magnetic field, the strength of the magnetic field, the force-free parameter along the magnetic field line, and the length of the magnetic

field line. The codes elaborated in Liu et al. (2016) were used to calculate T_w in our study.

The magnetic pressure in the corona was calculated by the following equation:

$$P_m = \frac{B^2}{2\mu_0}, \quad (4)$$

where B is the strength of the magnetic field derived by the NLFFF model.

If the constraining field declines rapidly enough with height, the flux rope or filament would become torus unstable (Kliem & Török 2006; Olmedo & Zhang 2010; Kliem et al. 2014). Numerous observational studies indicated that the torus instability plays a significant role in triggering the eruptions (e.g., Cheng et al. 2013, 2020; Zuccarello et al. 2014; Kang et al. 2023). To evaluate the decaying characteristic of the coronal magnetic field around the filament, we also calculated the decay index (n), which is defined by the following equation (Bateman 1978):

$$n = -\frac{d \ln B_t}{d \ln h}, \quad (5)$$

where B_t is the transverse component of the potential field, and h is the height above the photosphere. The potential fields (PF) in the corona were obtained with the Green function method with the vertical component of the photospheric vector magnetograms.

3. Result

3.1. Overview of the filament

In active region NOAA 12680, a filament with many overlying filamentary fibrils lay nearby a sunspot at around 06:50 UT on September 12, 2017. Figure 1a shows the observation of SDO/AIA 304 Å, and panel b is a zoomed-in region of panel a in an H α observation obtained by NVST. The filament has an inverted U-shaped structure and sits south of a sunspot with negative polarity. Many filamentary fibrils cross the filament. Fortunately, at this moment, the filament or the active region was situated near the solar limb when viewed from the STEREO-A telescope. Figure 1c exhibits the observation of STEREO-A/EUVI 195 Å band, and panel d is a zoomed-in region of panel c. Viewed by STEREO-A, it is hard to distinguish the filament in the limb observation. The arcade-shaped fibrils with many dark materials can be distinguished, however. Some large-scale coronal loops at the root of the sunspot can be also identified (see panel d).

3.2. Two jet-like activities before the filament eruption

3.2.1. The processes of two jet-like activities in SDO and NVST observations

The first jet-like activities occurred at around 06:00 UT. Figure 2 shows the detailed process of the first jet-like activity. The upper and middle rows show the observations of SDO/AIA 304 Å and 193 Å, while the bottom row is the LOS magnetograms from SDO/HMI. Many dark fibrils lay above the filament at 06:00 UT (see panel a1). Some brightenings marked by the black arrows first occurred north of the filament (see panels a1 and b1). At around 06:03 UT, the Y-shaped brightening structure can be found in the AIA 304 Å and 193 Å wavebands (see the

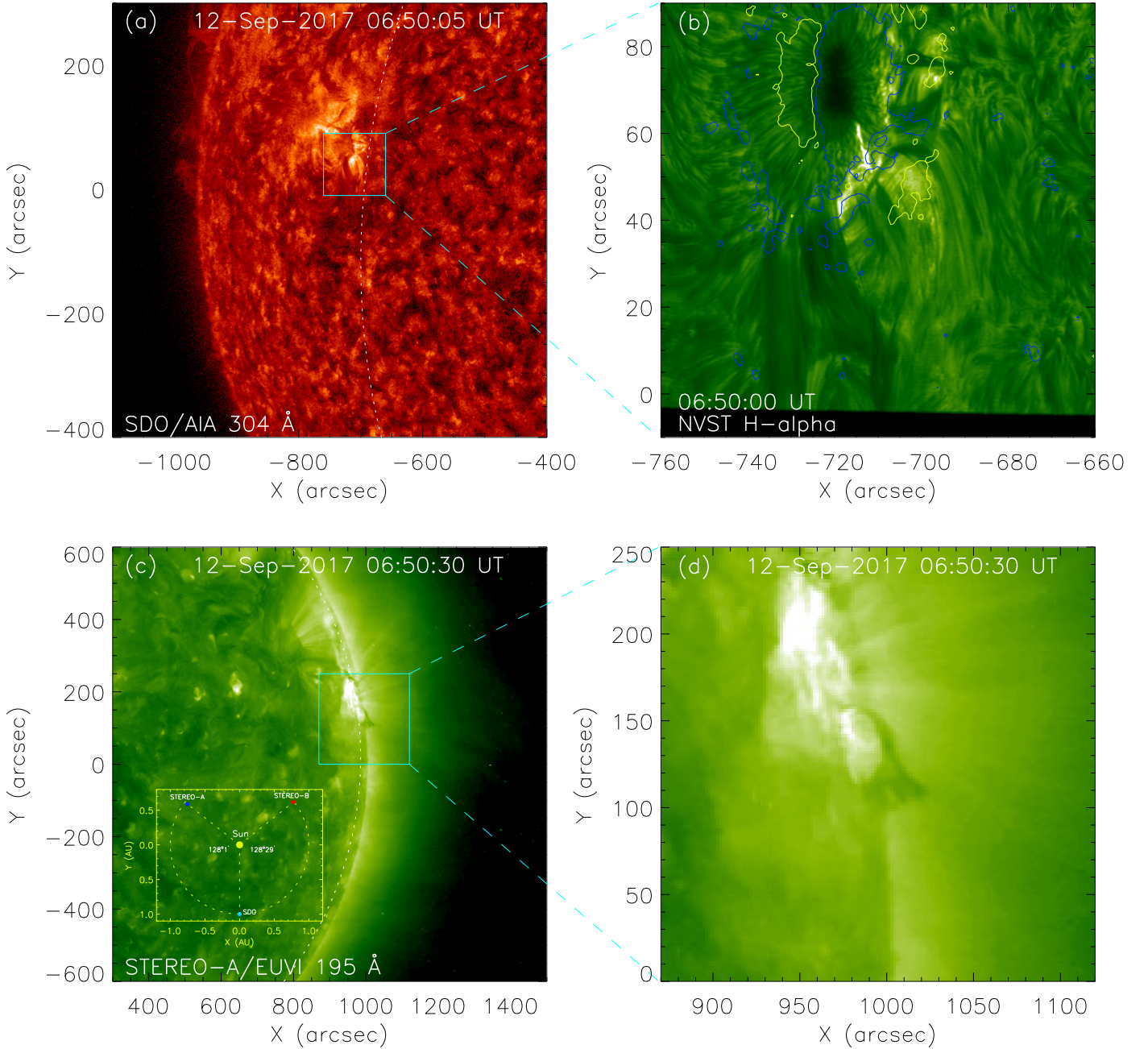


Fig. 1. Overview observations of the filament. (a): 304 Å image observed from SDO/AIA. The cyan box outlines the field of view of panel b. (b): H α images observed from NVST. The yellow and blue contours indicate the positive and negative magnetic field with levels of ± 100 G. (c): observations of STEREO-A/EUVI in 195 Å. The yellow box in the bottom left corner shows the relative locations of STEREO-A, STEREO-B, and SDO at 06:50 UT. The cyan box outlines the field of view of panel d. (d): zoomed-in region of panel c. The dotted white lines in panels a and c denote the same position on the Sun. An animation available [online](#) shows the observation of NVST H α during the period from 06:20 UT to 08:00 UT.

subregion in panels a1 and b1). With the occurrence of some brightenings, some overlying fibrils gradually slid along the filament and broke away from the initial place. Then, the twist was released along the lifted fibrils, as shown by the untwisting motions (see panels a2–a3 and b2–b3 and the animation of Fig. 2). The dotted white and black lines in panel a2 outline the winding structures during the release of the untwisted rotations. In the photosphere, some magnetic cancellation took place in the vicinity of the brightening (see panels c1–c3 of Fig. 2).

After half an hour, the second jet-like activity took place at the same place at around 06:40 UT. Figure 3 shows the detailed

evolution of the second jet-like activity. Panels a1–a4 are the H α observations obtained from NVST, and panels b1–b4 and b1–b2 are the corresponding observations of SDO/AIA 304 Å and 193 Å, respectively. Around 06:25 UT, numerous inverted U-shaped fibrils can be identified in the region of interest (see panels a1–a2, b1–b2 and c1–c2). Notably, several bunches of dark fibrils are situated above the inverted U-shaped fibrils, marked by the arrow in panel a1. With the contours of magnetic field displayed in panel a2, we consider that these dark fibrils were rooted in the positive polarities in the black box of panel a2. In the context of frozen-in plasma, these dark fibrils may

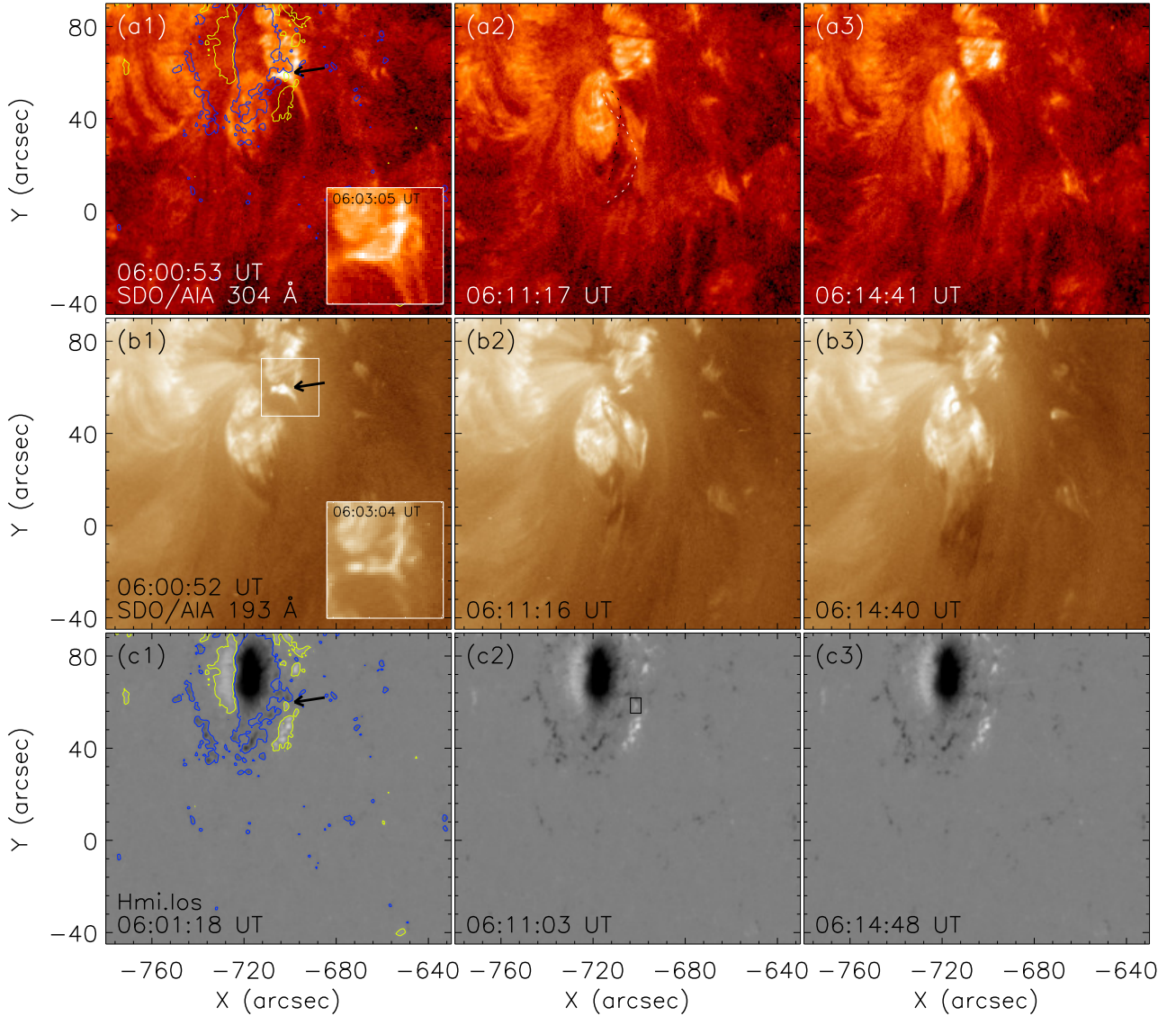


Fig. 2. First jet-like activity. (a1)–(a3): 304 Å images observed by SDO/AIA. The dotted white and black lines outline the twisted structures. (b1)–(b3): 193 Å images observed by SDO/AIA. The subgraphs in panels a1 and b2 are the corresponding images at around 06:03 UT. The white box in panel b1 outlines the FOV of these two subgraphs. (c1)–(c3): line-of-sight magnetic magnetograms from SDO/HMI. The yellow and blue contours indicate the positive and negative magnetic fields with the levels of ± 100 G, respectively. The black box in panel c2 outlines the region of the magnetic flux in Fig. 2c. An animation available [online](#) shows the first jet-like activity in the 304 and 193 Å wavelengths during the period from 05:55 UT to 06:18 UT.

represent magnetic fields that constrain the inverted U-shaped fibrils.

At first, some brightenings/Y-shaped brightening structures can be distinguished in some place as the first jet-like activities (see the white arrows in panels b2, c2, and d2). The constrained dark fibrils disappeared as the brightenings occurred. We attribute this phenomenon to the heating of cool plasma induced by magnetic reconnection. Additionally, many new moving fibrils formed around the brightenings, marked by the dotted yellow and blue lines in panel a3 (also visible in the animation of Fig. 1). Subsequently, these newly formed moving fibrils, accompanied by the inverted U-shaped fibrils containing dark material, ascended generally with some distinct untwisted rotations (see panels a3–a4 and b3–b4 and the animation of Fig. 3). The lifted fibrils are indicated by white arrows in panel a4. Eventually, an inverted U-shaped filament was clearly visible as these overlying fibrils were released (see panel a4).

To quantify the untwisted number released by the second activity, we traced the spatial structure to estimate the twist number from the untwisted rotations. Figures 4a–c show the untwisted rotation revealed by SDO/AIA 304 Å observations. By tracking the dark structure marked by the white arrows, we derived that the dark structure had rotated at least two rounds (see also the animation of Fig. 3). This means that the untwisted number released by the second activity can be more than two turns. On the other hand, we also made a time-distance diagram along the dotted-dashed white line perpendicular to the rolling tube. Panel d exhibits the time-distance diagram derived from a series of SDO/AIA 304 Å images. There are many distinct inclined stripes, which means that many dark structures went along the dotted-dashed line during the untwisted rotation. According to the imprint of the inclined stripes, the speed of these structures along the path was estimated to be about 47 km s^{-1} . With the assumption that the untwisted rotation kept

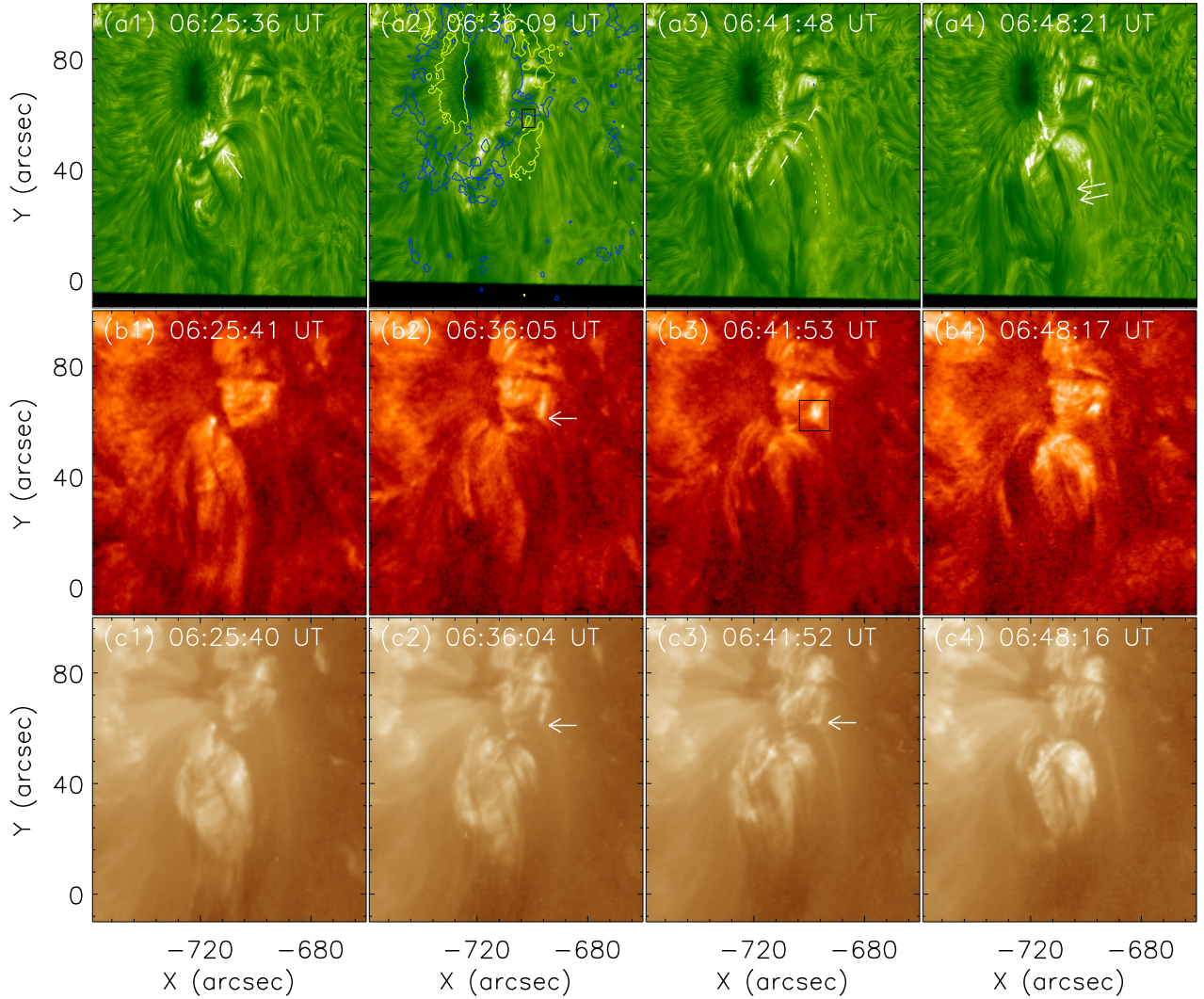


Fig. 3. Second jet-like activity. (a1)–(a4): $H\alpha$ images observed by NVST. The yellow and blue contours in panel a1 indicate the positive and negative magnetic fields with levels of ± 100 G, respectively. (b1)–(b4): $304 \text{ \AA}$ images observed by SDO/AIA. (c1)–(c4): $193 \text{ \AA}$ images observed by SDO/AIA. An animation available [online](#) shows the second jet-like activity in the $304 \text{ \AA}$ and $193 \text{ \AA}$ wavelengths during the period from 06:32 UT to 07:12 UT.

a constant speed and a constant radius, the untwist number released by the activity can be estimated by the formula of $T_n = vt/2\pi r$, where v , t , and r are the speed, duration time, and the radius of the rotation, respectively. The speed (v) of the rotation can be considered to be 47 km s^{-1} , derived from the time-distance diagrams. The activity was experienced during the period from around 06:45 UT to 07:06 UT, so that t equals about 21 min. The width (d) of the rotation marked by two dark asterisks in panel b can be estimated as about 8.7 mm, which indicates that $r = d/2$ is about 4.35 mm. According to the above values of the parameters and the formula, we can obtain that T_n is about 2.1 turns, which is consistent with the estimation based on tracing the special structure.

3.2.2. Some main observational phenomenons and interpretations

Figure 5a shows the variations in the positive magnetic flux in the black box of Figs. 2c2 and 3a2 and the mean intensity of AIA $304 \text{ \AA}$ in the box of Fig. 3b3. The mean intensity is normalized by its duration. The positive magnetic flux exhibited a decreasing

trend, which shows the magnetic cancellation between the positive flux and the upper negative flux (see Figs. 2c1–c3 and the animation of Fig. 6). Otherwise, there are two peaks in the AIA $304 \text{ \AA}$ intensity at around 06:05 UT and 06:41 UT, which indicate the brightenings caused by two jet-like activities. Panel b shows the time-distance diagram reconstructed by the NVST $H\alpha$ images along the dashed white line in Fig. 3a2. Many inclined structures marked by the two white arrows appear near the bottom of the time-distance diagram. Some dark structures marked by the yellow arrow at around 06:48 UT are the signal of material fibrils associated with the second jet-like activity. According to their inclination as outlined by two white dashed lines, these inclined structures and dark structures are closely related phenomena. As also evidenced by the animation of Fig. 1, they might show that the second jet-like activity originated from the brightenings marked by Figs. 3b2, c2, and c3 and was associated with the newly formed and moving fibrils.

In Figs. 6a1–a3, vector magnetograms from SDO/HMI are presented. Some magnetic flux emerged around the cancellation site. The yellow line depicts the variation in the positive flux within the white box of Fig. 6a1. These positive emerging fluxes

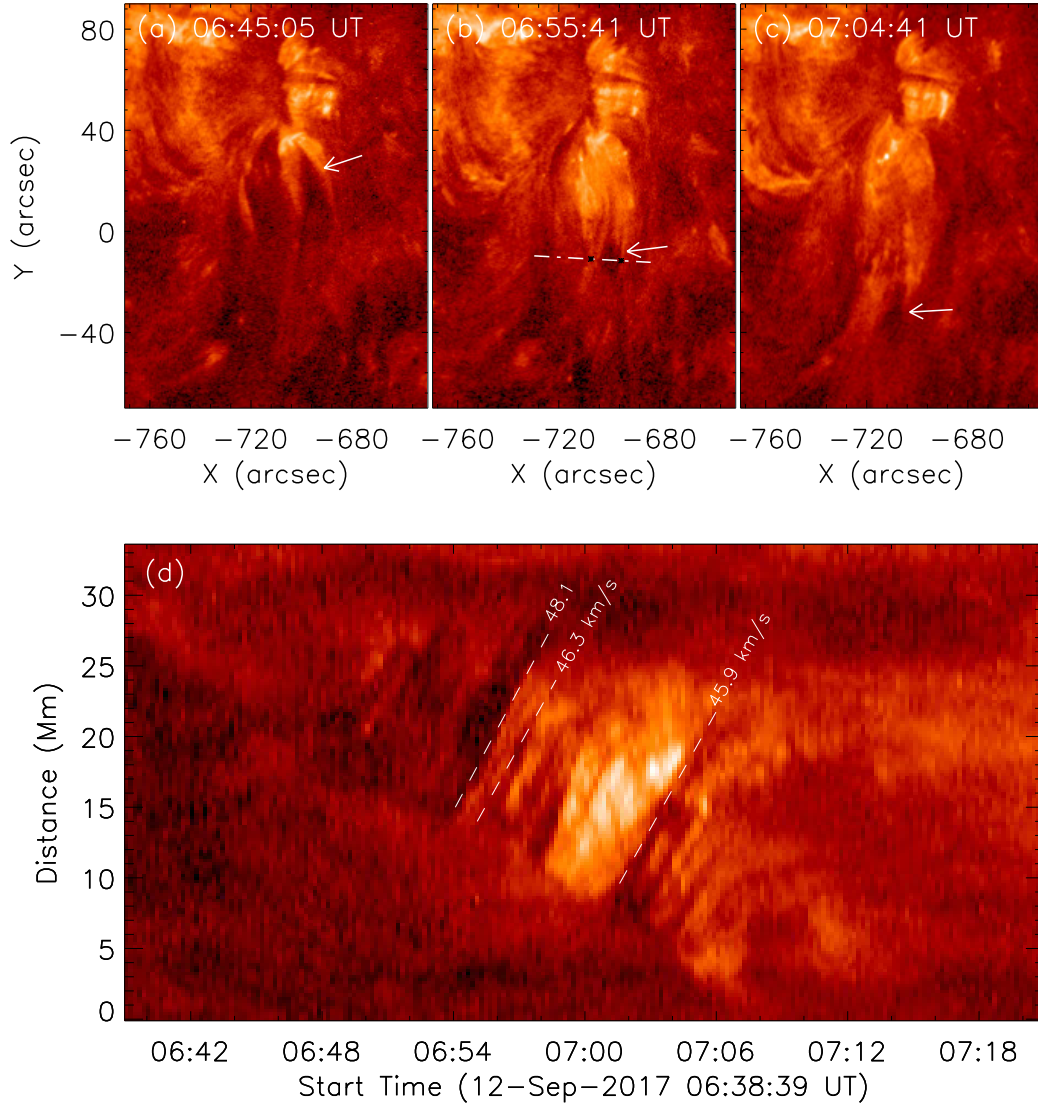


Fig. 4. Estimation of the twist number released by the second jet-like activity. (a)–(c): SDO/AIA 304 Å images at different moments. The white arrows mark the dark structure at a different moment. The dotted-dashed white line outlines the path for the time-distance diagram of panel d. The two black asterisks on the dotted-dashed white line mark the width of the rotation. (d): time-distance diagram reconstructed by SDO/AIA 304 Å observations along the dotted-dashed white line in panel b. The dashed lines mark some dark inclined stripes.

were associated with negative fluxes located north and in the proximity of the positive flux of cancellation (see the direction of the magnetic field, indicated by the blue/red arrows). Therefore, we consider that it was a new emergence of dipoles. The negative flux from the emergence had undergone cancellation in which the positive flux anchored the constrained magnetic field, as marked by the yellow arrow in Fig. 6a2. By 07:12 UT, it is evident that a substantial portion of the positive flux, indicated by the yellow arrows in panel a2, has been canceled almost entirely. This is consistent with the result of Fig. 5a. Figures 6b1–b2 show some selected magnetic field lines derived by the NLFFF model at 06:00 UT. Panel b1 shows the magnetic field lines from the top, and panel b2 shows the side view. The blue lines denote the magnetic field of the filament, while the white lines indicate some open magnetic fields sited near the filament. The pink lines denote the emerging magnetic field, while the red lines denote the magnetic field rooted in the positive fluxes. The red magnetic field lines are the constrained magnetic fields.

Based on the fact that some dipoles newly emerged nearby the positive polarity and that the positive and negative polarity of

the emerged dipole cancelled each other out, we suggest that the long magnetic field lines (the yellow lines) are probably formed by either the elevation of the serpentine magnetic field or by magnetic reconnection of two bunches of the U-shaped magnetic field, resulting in some magnetic cancellation at the junction (see panels c1 and c2). As the yellow lines reconnect with the open lines (the white lines), it would form two bundles of magnetic field lines (long inverted U-shaped open and short lines that link the yellow and blue lines in Fig. 3a2) and cause the (Y-shaped) brightenings at around the reconnection site. The twist in the red and yellow lines transfers to the open lines, which could cause the twist motion to release the twist in the open lines, such as in the event studied by Yang et al. (2019). Moreover, based on high-resolution observations, it is evident that some inverted U-shaped fibrils containing dark material were also released during the jet-like activity. This suggests that the inverted U-shaped open magnetic structures, accompanied by newly forming inverted U-shaped open lines, were released during the twist motion.

In these scenarios, our observations, including the newly emerging dipoles, magnetic cancellation, Y-shaped brightenings,

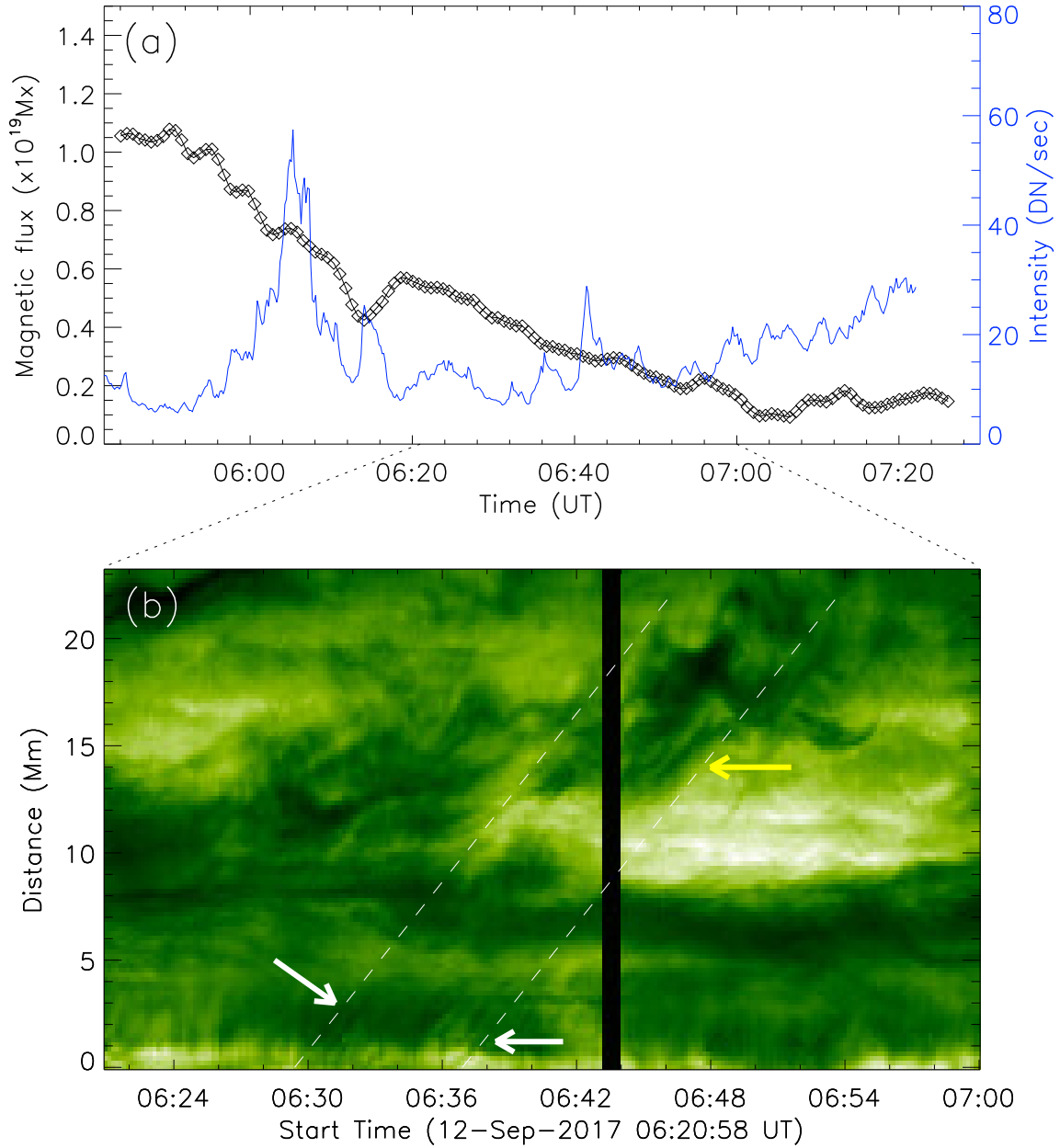


Fig. 5. Variations in some parameters. (a): variations in the positive magnetic flux in the black box of Figs. 1c2 and 2a1 and in the SDO/AIA 304 Å mean intensities in the box of Fig. 2b2. The mean intensities are normalized by the duration. (b): time-distance diagram derived from a series of NVST H α images along the dashed line in Fig. 2a2.

newly forming fibrils, and rotational motion, are well explained. Therefore, we infer that these two jet-like activities were caused by the aforementioned scenarios, resulting from magnetic reconnections caused by emerging flux. This process leads to the removal of constraint fields and the release of inverted U-shaped fibrils containing dark material.

3.2.3. Two overlying jet-like activities observed from STEREO-A

At the limb viewed by the STEREO-A observations, much dense material was ejected behind the dark arcade-shaped fibrils by the two jet-like activities. Figures 7a–c exhibit the 195 Å observations during the first activity. Much dark material marked by the white arrows was ejected aslant and fell back along the same path. Figures 7d–f are the 195 Å observations during the sec-

ond activity. The same phenomenon as in the first activity is observed. At around 07:33 UT, both the dark material and the arcade-shaped fibrils were cast away during the eruption (see panel f).

Figure 7g exhibits the time-distance diagram derived from 195 Å observations along the path of the dashed line in panel f. The dark material ejected by the activities shows a two-peak oscillation pattern before the eruption. The eruption occurred when the material fell back incompletely. The height of the two peaks along the slit path is estimated to be about 99.1 ± 2.2 mm and 112.3 ± 2.2 mm, which correspond to the heights of the jetted plasma above the solar limb of 43.2 ± 1.6 mm and 52.1 ± 1.6 mm, respectively. The uncertainties in the distances are estimated as two pixels of the image. When we assume that these materials were only affected by solar gravity after acceleration and experienced a free-fall motion, this requires that the

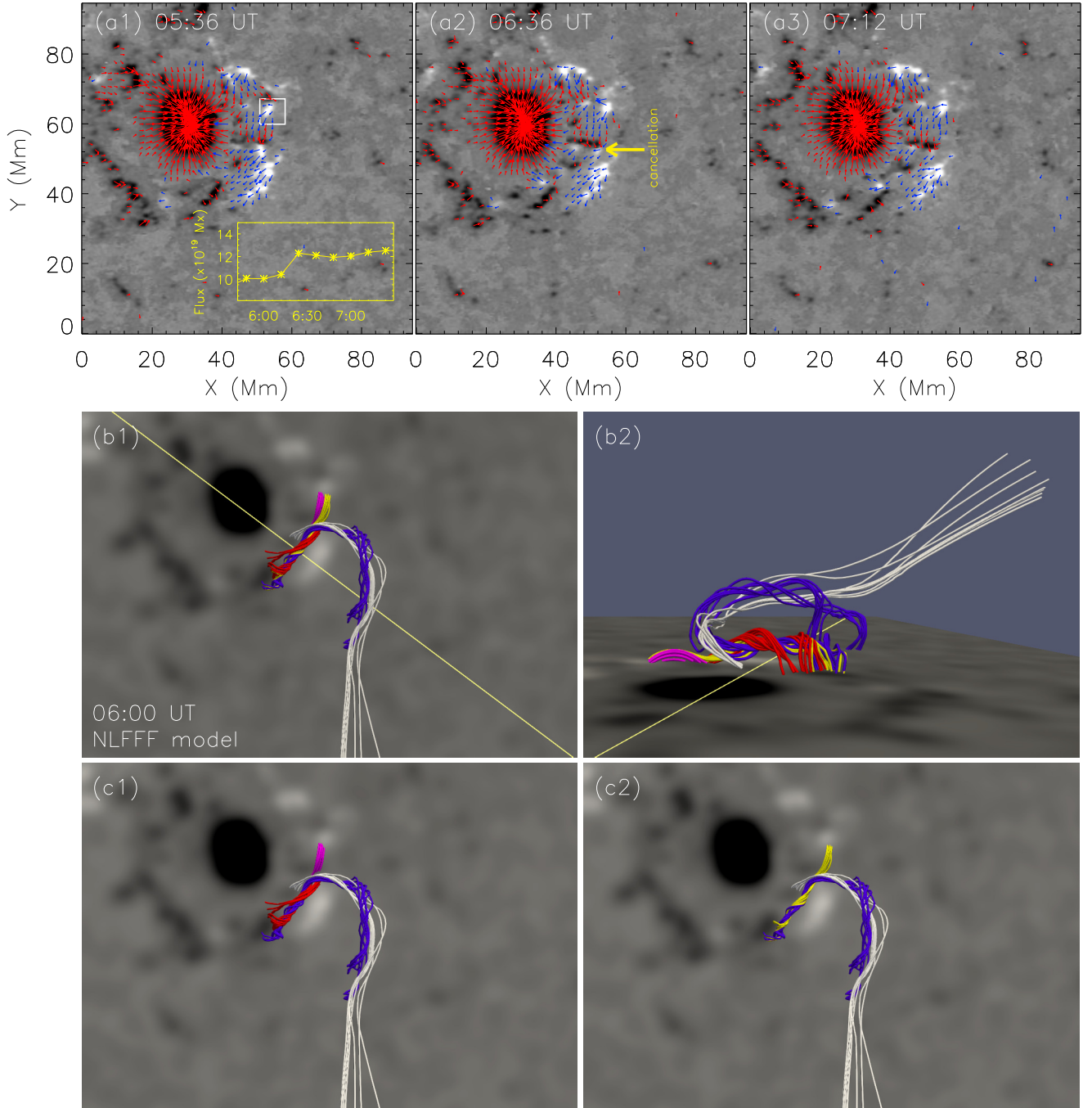


Fig. 6. Magnetic structures associated with two jet-like activities. (a1)–(a3): vector magnetograms. The blue and red arrows denote the transverse magnetic field with positive and negative vertical magnetic fields, respectively. The yellow box in panel a1 shows the variation in the positive magnetic flux in the white box of panel a. (b1)–(b2) and (c1)–(c2): magnetic field lines derived by the NLFFF extrapolation at 06:00 UT. Panels b1, c1, and c2 are a top view, while panel b2 is a side view. An animation available [online](#) shows the evolution of vector magnetograms during the period from 04:00 UT to 07:48 UT.

initial speeds of these materials were at least about 149.2 ± 2.6 and 162.9 ± 2.4 km s⁻¹, respectively. These values are comparable with the speeds of the plasma in the magnetic field during the jets in previous studies (Wang et al. 2018).

3.3. Eruption process of the filament

After the second jet-like activity, the filament became unstable and commenced its eruption around 07:20 UT. Figure 8 illustrates the eruption process of the filament. Initially, some bright-

enings occurred in the cancellation site, similar to the two jet-like activities around 07:14 UT, as indicated by the white arrows in panels a1 and b1. Intermittently, newly moving flows were ejected from the brightening point (see panel c1 and the animation of Fig. 8). Figure 9a shows the time-distance diagram along the blue dotted line in Fig. 8c1. It is noticeable that numerous dark stripes, marked by the yellow arrow, appeared between 07:14 UT and 07:18 UT before the filament started to lift, as indicated by the two blue arrows. This observation provides evidence that newly moving flows were intermittently ejected before the

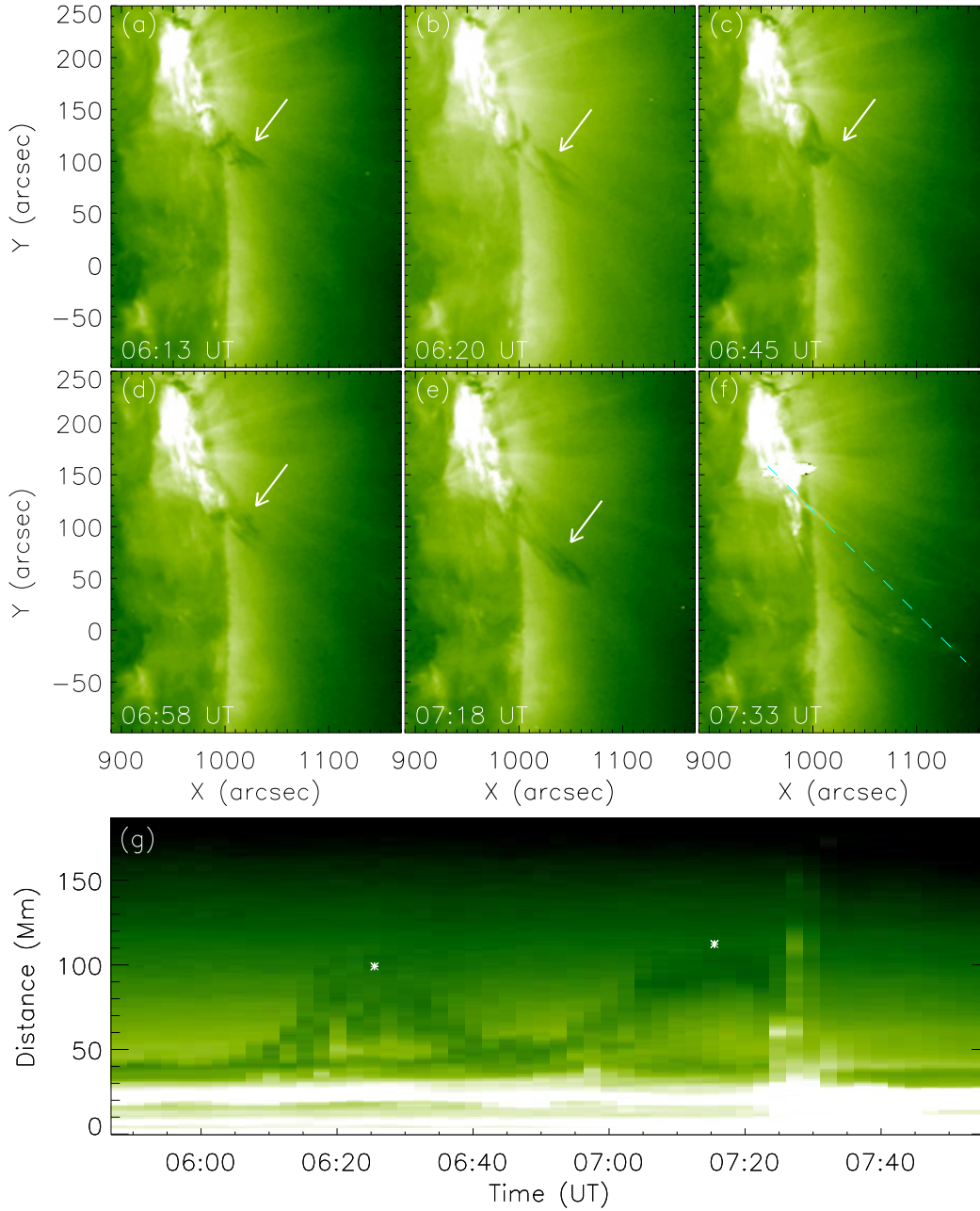


Fig. 7. STEREO-A 195 Å observations. (a)–(c): 195 Å observations for the first jet-like activity. (d)–(f): 195 Å observations for the second jet-like activity. The white arrows point to the dense dark material lifted by the jet-like activities. (g): time-distance diagram constructed by the STEREO-A observations along the dashed cyan line in panel f. The two white asterisks mark the highest points of the lifting dark material.

filament lifting. Combining the brightenings and these moving flows, we deduce that it is the same physical process involving magnetic reconnection as the two jet-like activities before the eruption, which also leads to a decrease in the constrained field.

Following this, the inverted U-shaped filament lifted from its middle part, as indicated by the blue arrows (see panels a2–a3, b2–b3, and c2–c3), and some brightenings occurred around the filament. Subsequently, it was ejected with an apparent rotational motion, its main axis marked by the dotted-dashed red line in panel b4. The rotation motion was clockwise when viewed from the top (see panels a4 and b4, and the animation of Fig. 8). Figure 9b presents the time-distance diagram constructed from SDO/AIA 171 Å images along the dashed line in Fig. 8b4. Many bright stripes in the diagram also indicate the rotation

motion during the eruption. In previous studies, this type of rotational motion was typically attributed to the eruption of a highly twisted flux rope (Amari et al. 2000; Fan & Gibson 2007). Furthermore, it could be inferred that the progenitor of the eruption, the filament, has a highly twisted structure. At around 07:31 UT, two footpoints of the filament also been brightened (marked by two blue circles in Fig. 8c4). They lie south of the flare ribbon.

Figures 9c–e exhibit the eruption process observed by the STEREO-A view. At around 07:25 UT, a tortuous structure representing the filament had been lifted away from the solar surface. After that, this structure had been ejected away along a non-radial path (see panels d–e). The angle between eruption path and radial direction was estimated to be about 57 degree (see panel c). This means that it experienced a non-radial

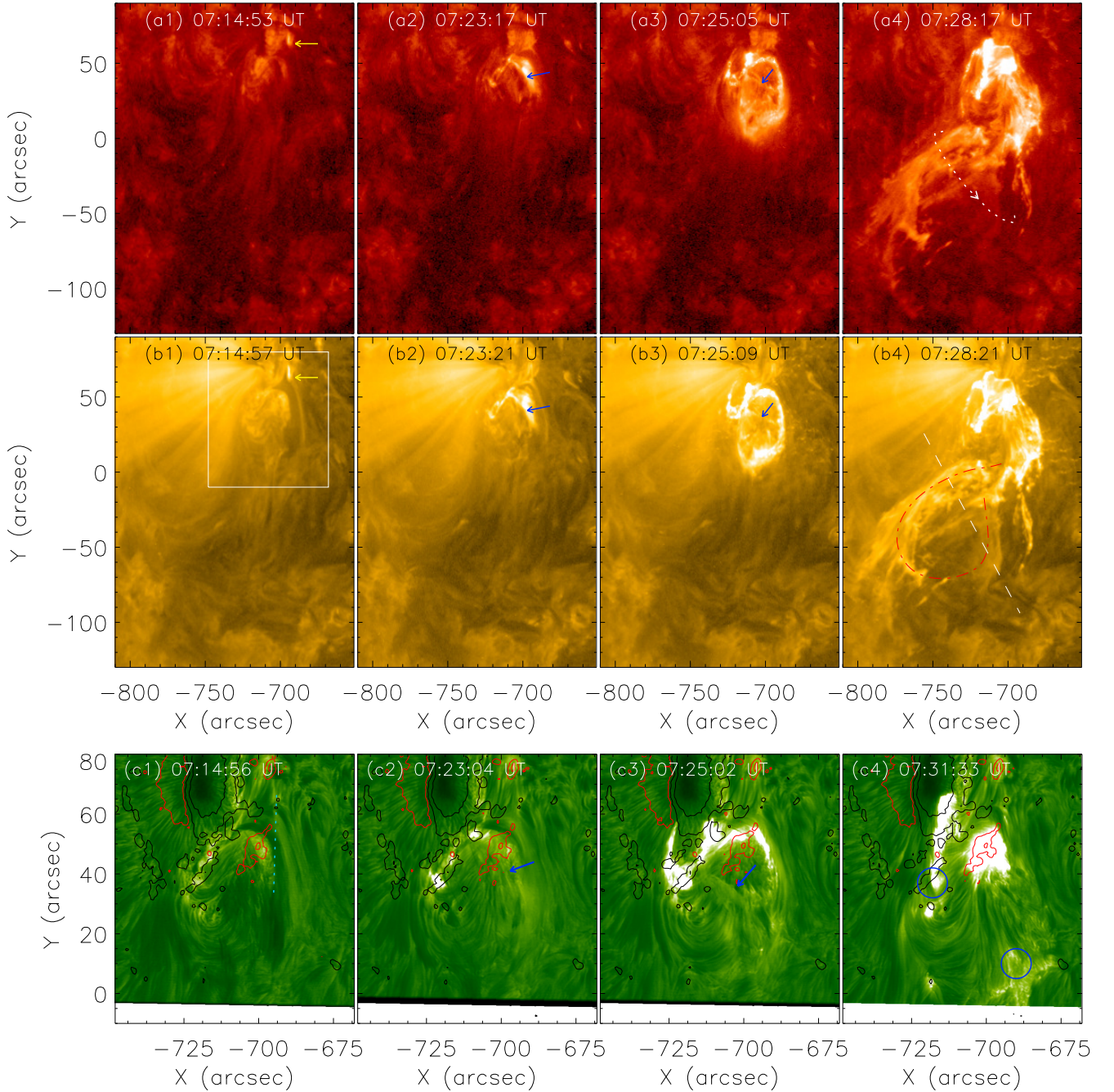


Fig. 8. Process of the filament eruption. (a1)–(a4): SDO/AIA 304 Å observations. (b1)–(b4): SDO/AIA 171 Å observations. The white box outlines the field of view of panels c1–c4. (c1)–(c4): NVST H α observations. The blue arrows point out the erupting filament. The red and black contours indicate the positive and negative magnetic field with levels of ± 100 G. The blue circles mark the brightenings associated with the footpoints of the inverted U-shaped filament. An animation available [online](#) shows the eruption process of the filament in 304 Å, and 171 Å wavelengths during the period from 07:12 UT to 07:52 UT.

eruption. Two threads connecting the ejecting structure with the solar surface were identified. This also further demonstrates that two footpoints of the filament are in the south of the post-flare loops, which is consistent with the finding of Fig. 8 and the extrapolated magnetic structures of the filament (see Fig. 5).

3.4. Decay index, magnetic pressure, and twist number

According to the methods described in the Sect. 2.2, we calculated the decay index, magnetic pressure, and twist number. Figures 10a–c exhibit the distributions of different

magnetic parameters at 07:00 UT in a cross-section cutting the filament and perpendicular to the solar surface. The yellow lines in Figs. 5b1 and b2 mark the intersection between the cross section and the solar surface. Panel a shows the decay index in the cross section and the selected magnetic field lines as Fig. 5, while panels c and d show the magnetic pressure and the twist number in the white rectangle box of panel a. It is evident that the filament exhibited a strong magnetic pressure and a high twist number. We consider the filament to be situated in a region with magnetic pressure exceeding 10^4 dyn/cm 2 . Specifically, we derive that the mean magnetic strength (magnetic pressure) of

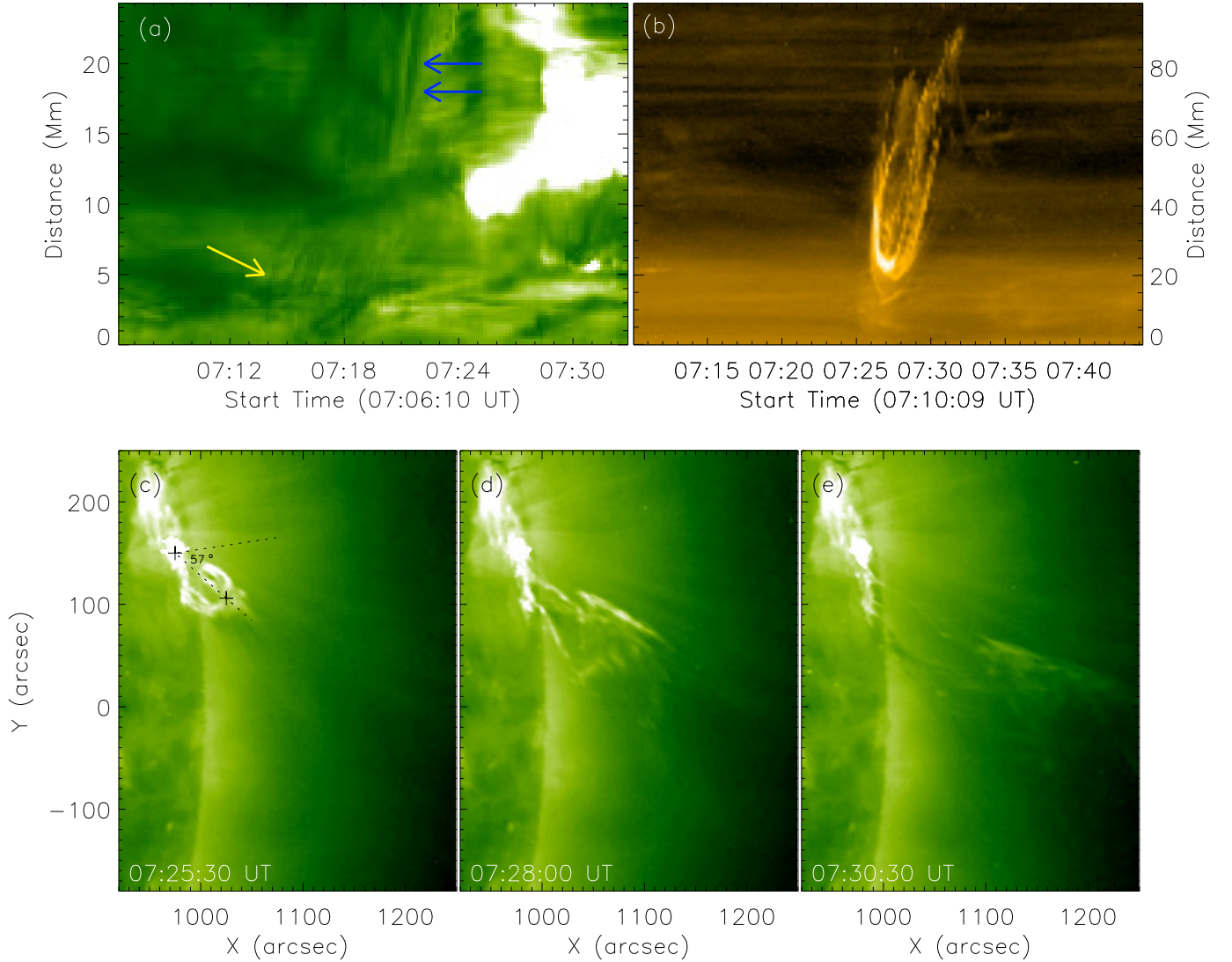


Fig. 9. Process of the filament eruption with STEREO-A observations. (a): time-distance diagrams constructed by the $H\alpha$ observations along the solid dotted light blue lines in Fig. 8c1. (b): time-distance diagrams constructed by the SDO/AIA 171 Å observations along the dashed white line in Fig. 8b4. (c)–(e): STEREO-A 195 Å observations.

the filament was approximately 540 Gauss (1.16×10^4 dyn/cm²), and the mean twist number was around 2.4 turns. This is comparable to the untwist number (2.1 turns) released by the second jet-like activity.

On the other hand, Fig. 10a shows the distribution of the decay index in the cross section, while the three-dimensional appearance is shown in panel d. At this moment, the entire filament was positioned below the level of 1.5, even below 1.0. For a more detailed analysis, the selected magnetic field lines representing the filament were marked by 14 white points (see panels d and e), which also indicate the location of the filament. Panel f displays the height of these white points and overlays the distribution of the decay index with height. We derived that the maximum height of the filament is about 12 mm. Furthermore, it is evident that the filament was situated in the region below the decay index of 1.0. To ensure accuracy in estimating the filament height and to avoid inaccuracies in the NLFFF model (Fleishman et al. 2017), observations from two perspectives were used to estimate the height of the filament around 07:15 UT (see panels g and h). By using the routine `scc_measure.pro` in the SSW package (Thompson 2009;

Cheng et al. 2020; Guo et al. 2021), the height of the filament was derived by identifying the filament structures in two different viewing observations. The observational filament is marked by the white plus signs in panels g and h. Panel i displays the derived height of the filament, demonstrating that the filament was located below 12 mm. This is consistent with the height derived by the NLFFF model. Therefore, the torus instability plays a minor role in triggering this filament eruption.

However, as the rising of the filament after the filament eruption is initiated, it starts to ascend into regions with a decay index exceeding 1.5. Throughout the filament eruption, the reconnection in the flare current sheet below the filament may play a more crucial role in accelerating the eruption, possibly coupled with torus instability, as discussed in previous works (Cheng et al. 2020, 2023). This interplay of processes might explain why the filament eruption was eruptive and not confined.

Figures 11a and b show the distribution of magnetic pressure in the zoomed-in region of Fig. 10a at 05:48 UT and 07:12 UT, respectively. Compared with these two panels, an attractive shrinkage marked by the white arrow was found over the filament, which means that the gradient of the magnetic

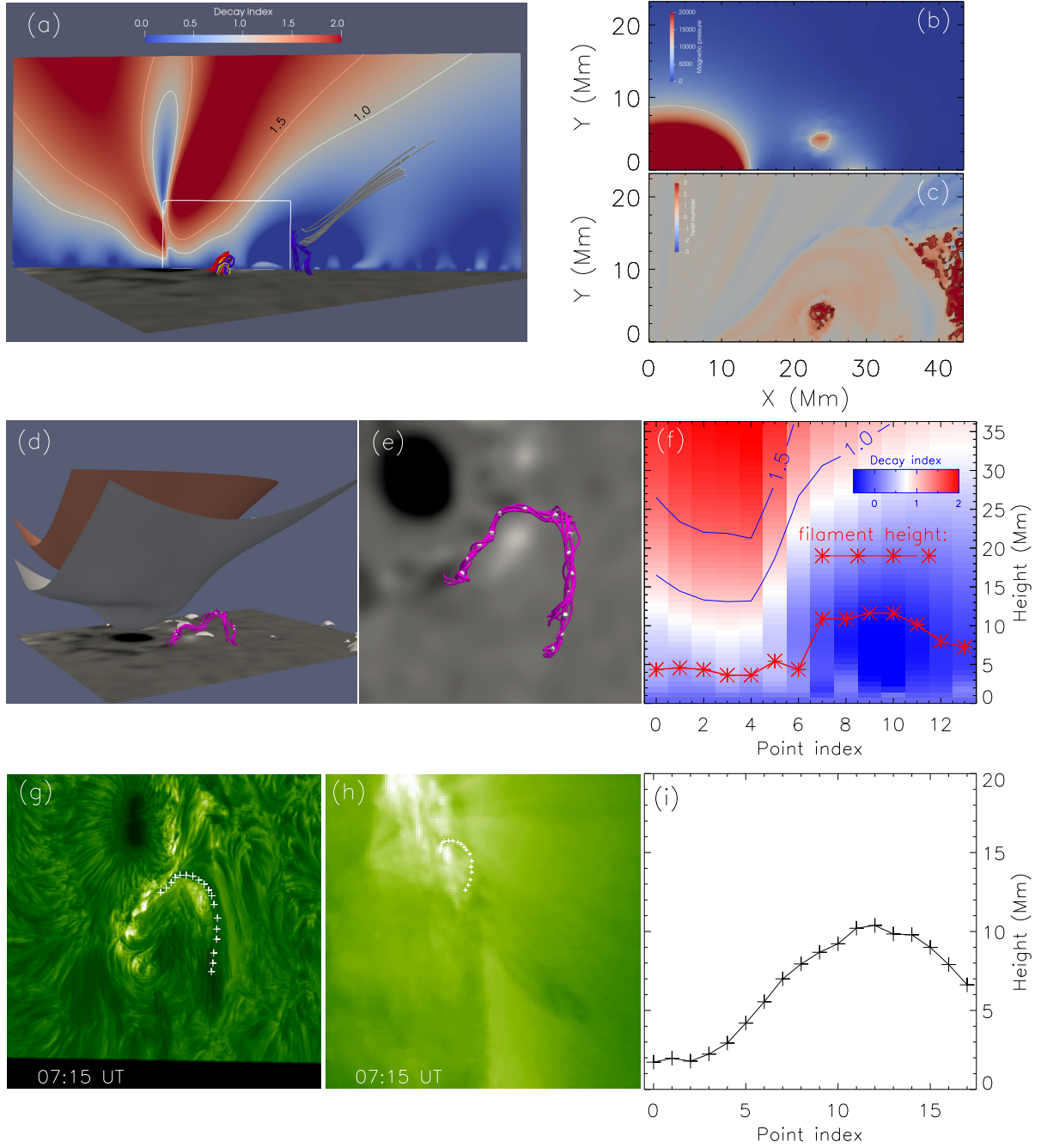


Fig. 10. Magnetic properties before the filament eruption. (a): distribution of the decay index in the cross section, superimposing the selected magnetic field lines from Fig. 6. The cross section is perpendicular to the solar surface along the yellow line in Figs. 6b1 and b2. The contours indicate the decay index values of 1.5 and 1.0. The white rectangle box outlines the region of panels b and c. (b): distribution of magnetic pressure, with white contours denoting magnetic pressure at $10\,000\text{ dyn/cm}^2$ ($\sim 500\text{ Gauss}$). (c): twist number, with the black contour outlining the twist number of two turns. (d): selected magnetic field lines representing the inverted U-shaped filament and three-dimensional contours of the decay index at 1.5 and 1.0. (e): selected magnetic field lines representing the inverted U-shaped filament seen from a top view, overlapping with some selected white dots. The white dots in panels d and e mark the filament structure. (f): height of the filament marked by the white dots. The background shows the decay index with the height at the corresponding points. The contours represent decay index values of 1.5 and 1.0. (g): NVST H α observaion at 07:15 UT. (h): corresponding STEREO-A 195 Å observaion. The white plus signs mark the same structure representing the filament seen from different views. (i): Height of the selected white plus signs.

pressure increased in that place. To qualitatively analyze this, we calculated the mean gradient of the magnetic pressure in the black box of Fig. 11a. Panel c exhibits the variation in the mean gradient magnetic pressure in the black box. At around 05:48 UT, before the two overlying jet-like activities, the mean gradient of the magnetic pressure was about $1.2 \times 10^{-5}\text{ dyn/cm}^3$,

while it is about $2.3 \times 10^{-5}\text{ dyn/cm}^3$ at around 07:12 UT after the two overlying jet-like activities. The gradient of the magnetic pressure generally displayed a gradual increase with time during the periods of the two overlying jet-like activities. This suggests that two overlying jet-like activities releasing the constraining magnetic fields (the red lines in Fig. 5) would increase the

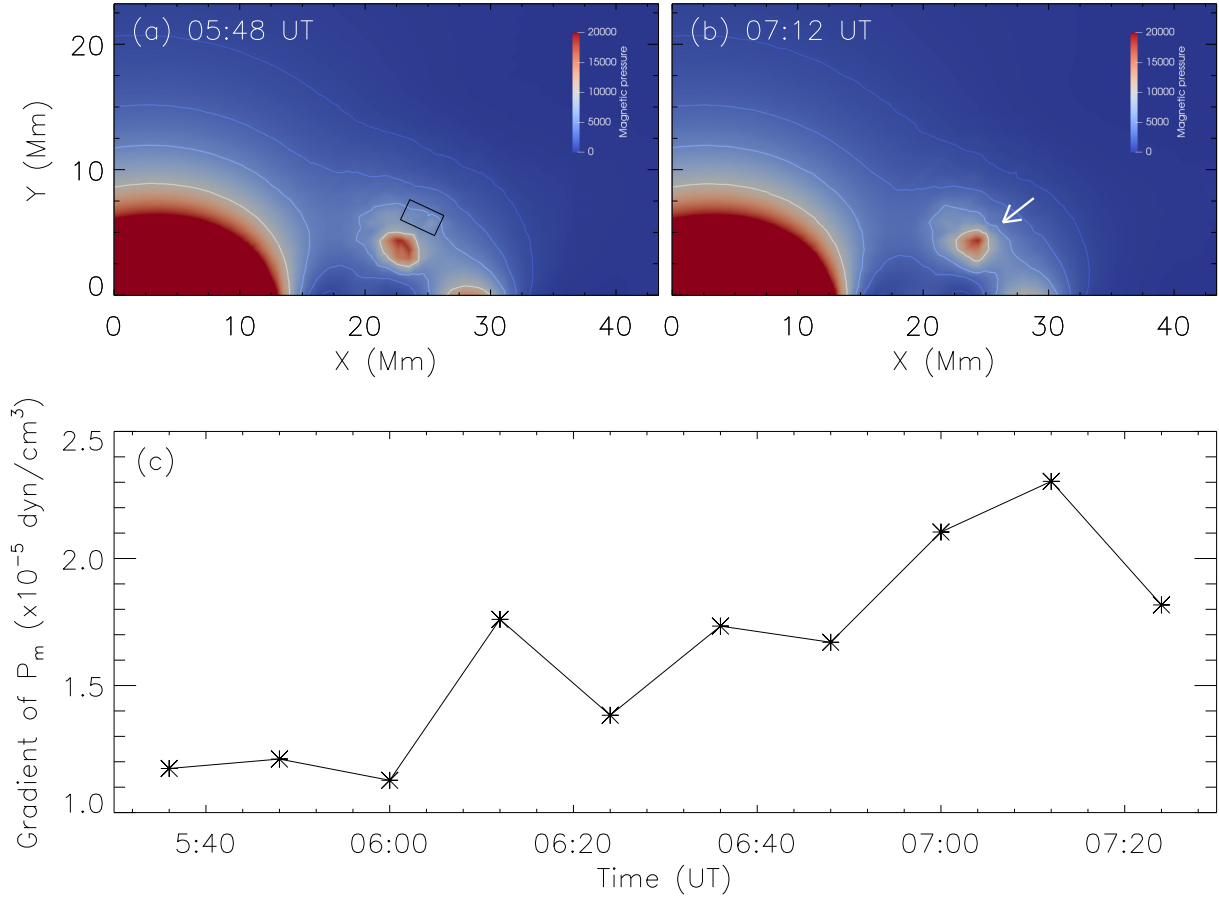


Fig. 11. Distribution of the magnetic pressure in the white box of Fig. 9a. (a)–(b): magnetic pressure at 05:48 UT and 07:12 UT. The contours outline the magnetic pressure with levels of 1000, 2000, 5000, and 10 000 dyn/cm². (c) Variation in the mean gradient of the magnetic pressure in the black box of panel a.

gradient of the magnetic pressure over the filament. With the increase in the gradient of the magnetic pressure over the filament and the decrease in the constraining magnetic fields, it becomes increasingly difficult to stabilize the highly twisted filament and prevent its eruption. Therefore, the decrease in the constrained magnetic fields caused by the two overlying jet-like activities is the key reason for the filament eruption.

4. Summary and discussion

We investigated an inverted-U shaped filament eruption and its two precursory activities in active region NOAA 12680 on September 12, 2017. By using different ground-based and space-based telescopes, we studied some precursory activities before the filament eruption and the process of its eruption. Based on the magnetograms observed by SDO/HMI and the extrapolations, we also analyzed the magnetic properties to explore the physical mechanism for the initiation of the eruption. Our main results are listed below.

(1) Two precursory jet-like activities took place before the eruption of the inverted-U shaped filament, which lifted some dense materials to about 50 mm above the solar limb. The activities were caused by the magnetic reconnection, which in turn was caused by the emerging flux. Untwisted rotation was found during the two events, and the twist number of at least two turns was released in the second event.

(2) Before the filament eruption, some brightenings and newly moving flows occurred in the same location as the onset of

two jet-like activities, indicating the same physical process as for two jet-like activities. Based on observations from the STEREO-A view, the eruption appears to be nonradial.

(3) Based on the extrapolation, we determined that the filament lay under a height corresponding to a decay index of 1.0, exhibiting strong magnetic fields and a high twist number before its eruption. The gradient of the magnetic pressure displayed a gradual increase with time before the filament eruption.

In our study, we observed two jet-like precursors, brightenings, and newly moving flows before the eruption of the filament. These phenomena are attributed to the same physical process involving magnetic reconnection, leading to magnetic cancellation and an increase in the gradient of magnetic pressure (see Figs. 5a and 11c). All these precursors contribute to the release of constrained magnetic fields situated on the positive polarity within the black box in Fig. 2. Consequently, we consider these events as homologous physical processes, and they probably play a crucial role in the onset of the filament eruption.

Figure 12 illustrates the process of releasing constrained magnetic fields through magnetic reconnection initiated by the emergence of new magnetic flux. Initially, the inverted U-shaped filament (blue lines) is constrained by some magnetic fields (red lines; see panel a). Some magnetic dipoles emerge nearby the positive constraining magnetic field. In one scenario, the positive polarity of the constraining field may connect with the negative polarity on the subsurface. The elevation of these serpentine magnetic fields would result in magnetic cancellation in the photosphere, producing long constraining magnetic fields (red lines;

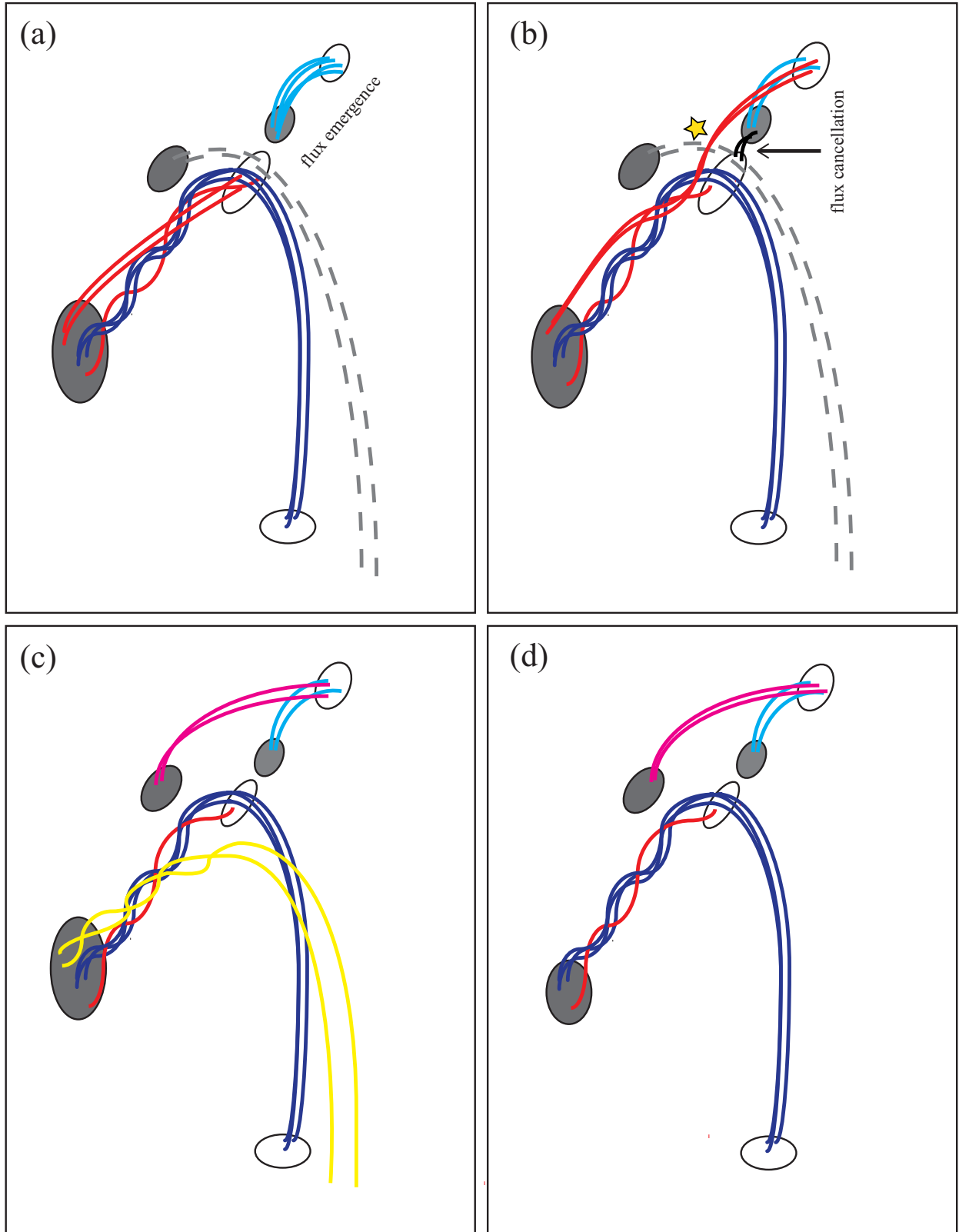


Fig. 12. Cartoon showing the release of the constraining magnetic field through continuous magnetic reconnection. The gray cycle denotes the negative magnetic flux, and the white cycle denotes positive magnetic flux. The blue lines denote the main body of the inverted U-shaped solar filament. The red lines denote the constraining magnetic fields, and the dashed gray lines denote the open field lines.

see panel b). In another scenario, the newly emerging magnetic fields reconnect with the constraining magnetic fields, forming long constraining magnetic fields (red lines) and shorter mag-

netic field lines (black lines; see panel b). Due to the high curvature of the short magnetic fields, these shorter lines sink beneath the surface, leading to magnetic cancellation (see panel b). In the

subsequent step, the long constraining magnetic fields undergo reconnection with open magnetic fields (dashed gray lines; see panel b), resulting in the formation of the twisted open magnetic fields (yellow lines) and short magnetic field lines (pink lines; see panel c), consistent with newly forming fibrils marked by the dotted yellow and blue lines in Fig. 3a3 during the second jet-like activity. These newly forming open magnetic fields, along with some already existing open magnetic fields, are released, involving inner magnetic reconnection. When the twist within the open magnetic field is released, untwisted motions become observable in observations. These episodes are consistent with the observation of two jet-like activities before the eruption. As more constraining magnetic fields are progressively released, the inverted U-shaped filament becomes constrained by fewer magnetic fields (see panel d). When the constraining magnetic fields can no longer maintain stability for the inverted U-shaped filament, the twisted filament likely erupts.

The magnetic structure of the filament has been debated for several decades. It is unclear whether it is a flux rope (Kuperus & Raadu 1974; Aulanier & Demoulin 1998) or a sheared arcade (Kippenhahn & Schlüter 1957; Malherbe & Priest 1983). Analyzing 571 filaments observed by SDO/AIA, Ouyang et al. (2017) found that 89% of the filaments are supported by flux ropes and 11% by sheared arcades. In our study, the distinguishing untwisted rotation was found in both two jet-like activities, while the untwist number released by the second activity could be more than two turns. On the other hand, according to the NLFFF extrapolation, a twisted structure representing the filament was also obtained, and the twist number could be about 2.4 turns (see Fig. 10d). Furthermore, the eruptive filament showed a rotating motion during its eruption (see Fig. 8). These clues suggest that this active region filament was a highly twisted flux rope and not a sheared arcade, which is consistent with the previous study (e.g., Yan et al. 2015; Xue et al. 2017; Wang & Liu 2019).

Through the estimates by tracing the untwisted rotation and NLFFF model extrapolation, we were able to derive that the twist of the filament was at least two turns before its eruption, which exceeds the threshold of the kink instability (Hood & Priest 1979, 1981; Török & Kliem 2003). Some authors also found that the filaments or prominences had a highly twisted magnetic structure (e.g., Yan et al. 2014; Xu et al. 2020). This manifests that a highly twisted filament can remain and does not erupt. The reason for this phenomenon might be that the high gravity of dense plasma or some strong constrained magnetic field prevents the filament from erupting. In our study, we suspect that many filamentary fibrils over the filament and the magnetic fields that are anchored in the positive polarity marked by the black box in Fig. 2c2 (represented by red lines in Fig. 5) might play a key role in preventing the highly twisted filament from erupting.

The triggering mechanism of the filament eruptions is crucial for understanding solar storms and forecasting interplanetary weather. On one hand, previous studies have suggested that torus instability, coupled with the tether-cutting mechanism, plays a key role in initiating eruptions. The tether-cutting mechanism causes the slow-rise phase, while the torus instability mechanism triggers the main acceleration phase (e.g., Cheng et al. 2013, 2020; Woods et al. 2018; Chen et al. 2018). On the other hand, Wyper et al. (2017) proposed that magnetic breakout is a universal model for solar eruptions on different spatial scales. In the breakout model, magnetic reconnection above the main body, removing the constrained magnetic field, is involved at the onset of eruption. However, the driver or trigger for this magnetic reconnection, perhaps originating from photospheric flows or

another source, remains unclear. In our study, two jet-like precursory activities and some brightenings served as signals of magnetic reconnection, where the reconnection removed the constraining magnetic field for the filament. As the constrained magnetic fields were gradually removed, the highly twisted filament became unstable and erupted. This part is consistent with the breakout mechanism. On the other hand, we also observed that these precursory activities were associated with the emergence of new magnetic flux. In our case, the magnetic reconnection, which removed the constraining magnetic field, was caused by the newly emerging magnetic flux. This provides a more detailed episode for understanding the onset mechanism of the filament eruption. These two jet-like activities not only eliminated some dense plasma pressing the filament, but also released the constraining magnetic field around the filament, thereby increasing the gradient of the magnetic pressure. In summary, these precursor activities created favorable conditions for the eruption of the highly twisted filament by removing the constraining magnetic field and some dense plasma.

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