Apparent Footpoint Rotation and Writhe of Double Hot Channels in a Solar Flare

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Abstract

We investigate the M6.5 class flare (SOL2015-06-22T18:23) occurring in NOAA Active Region 12371 on 2015 June 22. This eruptive flare is associated with a halo coronal mass ejection with a speed of 1200 km s\(^{-1}\). The 94 Å observations by Atmospheric Image Assembly onboard Solar Dynamics Observatory show that one hot channel first rises up, then forms a kinking structure with negative crossing and erupts, which is followed by the eruption of another kinking hot channel with negative crossing at a similar location between the start and peak times of the flare. Consistent with the standard flare model, footpoint drifting of the two hot channels is observed during the eruption. More interestingly, the two footpoints of the first hot channel continue to drift and display an apparent clockwise rotation after leaving the area of the hook-shaped flare ribbons. This apparent rotation is along the high-Q region of the log Q map derived from the nonlinear force-free field extrapolation. Our analysis suggests that the apparent rotational motion is likely caused by magnetic reconnection between the first hot channel and the surrounding magnetic fields at the high-Q region during the unwrithing process. The unwrithing of the second hot channel is accompanied by a significant slipping motion of its right footpoint.

Unified Astronomy Thesaurus concepts: Solar x-ray flares (1816); Solar extreme ultraviolet emission (1493); Solar magnetic reconnection (1504)

Supporting material: animations

1. Introduction

Solar flares, prominence/filament eruptions, and coronal mass ejections (CMEs) are the three most violent solar activities, and they usually occur together. Magnetic flux ropes (MFR) are generally considered to be the core structure of various explosive activities in the solar atmosphere, which are usually manifested as a set of magnetic field lines wrapping around its central axis (Zhang et al. 2012; Liu 2020). The eruption of MFR can be driven by the ideal MHD instabilities, and the most popular ones include kink instability (Fan & Gibson 2003, 2004; Török et al. 2004) and torus instability (Klimchuk & Török 2006). When the twist of the MFR exceeds the critical value, kink instability occurs, and the axis of the MFR is rapidly deformed, transforming part of the twist into writhe. The typical critical value is around 3.5 \(\pi\), and changes with different aspect ratios of the loops involved (Baty 2001; Török et al. 2014). The torus instability occurs when the inward restoring force generated by the background magnetic field decreases faster than the outward Lorentz force (Klimchuk & Török 2006; Fan & Gibson 2007). On the other hand, mechanisms involving magnetic reconnection can also trigger the explosion of the MFR. Magnetic reconnection occurring above and below the MFR corresponds to the break-out model (Antiochos et al. 1999; Lynch et al. 2008) and the tether-cutting model (Moore et al. 2001; Jiang et al. 2021), respectively.

Analysis of an MHD simulation of a coronal MFR confined by a helmet streamer by Liu & Su (2021) shows that the enhanced overlying reconnection and explosive flare reconnection play important roles in driving the slow rise and fast rise of the MFR, respectively. Recent studies have discovered double-decker (Liu et al. 2012) and multiple magnetic flux rope systems (Li et al. 2017; Hou et al. 2018; Su et al. 2018), and magnetic reconnection occurring within the system can also lead to the explosion of the MFR (Awasthi et al. 2018).

Filament, filament channels, coronal cavities, and sigmoid structures can all be regarded as observational evidence of MFRs (Low & Hundhausen 1995; Mackay et al. 2010; Wang & Stenborg 2010; Green et al. 2011; Su & van Ballegooijen 2012). Hot channels are recently discovered observational evidence of magnetic flux rope, which is observed in Atmospheric Image Assembly (AIA) high-temperature passbands (i.e., 94 and 131 Å), and generally appears above the magnetic polarity inversion lines (PIL) with the central axis clearly separated from the PIL in height (Zhang et al. 2012; Cheng et al. 2014; Cheng & Ding 2016). A hot channel is usually a curved cylinder or writhed channel structure, and its shape is different as viewed from different angles (Zhang et al. 2012; Cheng et al. 2013; Liu 2020). A statistical study shows that about half of the eruptive flares are associated with hot channels (Nindos et al. 2015). Some hot channels exist before the eruption (Liu et al. 2018), while others are formed during the eruption (Shen et al. 2017). Filaments are often observed under the hot channels (Cheng et al. 2014). Magnetic field modeling by Liu et al. (2018) shows that the observed hot channel corresponds to the MFR above a hyperbolic flux tube.
the magnetic fields under which correspond to the observed filament. Recently, multiple hot channels and filaments have been observed during a solar flare (Wang et al. 2018). Events with a single hot channel (Liu et al. 2013) or multiple hot channels without filaments (Shen et al. 2017) have also been reported.

Writhe is a general property of kink instability (Kliem et al. 2004), which is a measure of how much the flux rope’s axis itself is twisted. Some filaments display an “inverse γ” shape (kinking structure) during the eruption, which is due to writhe and is commonly regarded to be evidence of the kink instability (Rust & LaBonte 2005; Török & Kliem 2005; Gilbert et al. 2007). During the failed filament eruption on 2002 May 27 reported by Ji et al. (2003), the filament writhe early in the event, which is followed by a period of rapid expansion and an apparent untwisting motion of the entire filament apex (Alexander et al. 2006). Török & Kliem (2005) have simulated this event using a kink unstable flux rope model, which can reproduce the observations well, including the writhe motion and the apparent untwisting motion. Kinking structure has also been observed in partial filament eruptions (e.g., Liu et al. 2008). Fan (2005) has developed a three-dimensional (3D) MHD model, in which a twisted magnetic flux rope slowly emerges into a pre-existing coronal potential field. The writhe motion of the flux rope makes it easier for the flux rope to break away from the confinement (Liu et al. 2007; Gilbert et al. 2007). When the simulation time is long enough, the erupting magnetic flux rope will break into two parts, and thus a partial eruption occurs (Gibson & Fan 2006; Gilbert et al. 2007). In the event on 2003 June 12, two kinked filaments appeared in the same area 10 minutes apart, evolved in the same way, and eventually erupted together, and the locations of the two footpoints are the same (Liu & Alexander 2009).

The two-dimensional standard CME/flare model (CSHKP) (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976) has recently been extended to three dimensions by Aulanier et al. (2012) and Janvier et al. (2013). In this 3D model, the magnetic flux rope is surrounded by a quasi-separatrix layer (QSL) with drastically changing magnetic field line connectivity (Demoulin et al. 1996). Magnetic reconnect is likely to occur at the QSL due to the large magnetic gradient. The footpoints of QSL are double J shaped, and the curved part of the end surrounds the footpoints of the MFR (Démoulin et al. 1996). Savcheva et al. (2015, 2016) have confirmed that the footpoints of QSL are related to the observed flare ribbons, and the footpoint motion of the hot channel during the eruption will form hooks at both ends of the flare ribbon (Cheng & Ding 2016; Chen et al. 2019). In the slow rise phase or precursor phase, the hot channel can also appear as a kinking structure and then evolve into a loop with the eruption (Liu et al. 2010; Cheng & Ding 2016; Chen et al. 2019). Xue et al. (2016) has found that magnetic reconnection between the erupting filament and the surrounding magnetic fields can release its twist. If the rotation direction of the erupting filament is opposite to that caused by kink instability, the writhe can be released (Liu 2020). In this article, we investigate the apparent footpoint rotation and writhe of two hot channels during an M6.5 class solar flare. The observations are presented in Section 2. In Section 3, we carry out a magnetic topology analysis. Discussion and summary are given in Section 4.

2. Observation

2.1. Instrument and Overview

Solar Dynamics Observatory (SDO)/AIA can simultaneously observe the solar atmosphere from the photosphere to the corona in ten narrow UV and EUV channels. The temporal cadence is 12 and 24 s for the EUV and UV passbands, respectively. The pixel size is 0.6" (Lemen et al. 2012). In this study, the kinking structure of two hot channels can be identified in 94 and 131 Å images by AIA. The observations in 304 Å are adopted to understand the evolution of the filament. SDO/HMI provides the photospheric magnetic fields of the flaring region with a pixel size of 0.5" (Schou et al. 2012). The vector magnetograms of Space weather HMI Active Region Patches (SHARPs; Bobra et al. 2014), with a cadence of 12 minutes are preprocessed and used as the boundary conditions of the “weighted optimization” code (Wiegelmann 2004) to extrapolate the 3D nonlinear force-free field (NLFFF) and potential field. GOES observations reveal changes in soft X-ray (SXR) during the flare (Figure 1(a)).

The kinking structure of two hot channels is observed between the start and peak times (18:23 UT) of the M6.5 class flare, as shown in the GOES soft X-ray light curve in Figure 1(a). The apparent footpoint rotation of the first hot channel begins (HC1, yellow box) before the appearance of the second kinking hot channel (HC2, gray bar). The photospheric vector magnetogram of NOAA AR 12371 is presented in Figure 1(b). In the early acceleration phase of the flare, all activities take place at the major sunspots in the east, and some brightenings extend to the adjacent western sunspot later on. Bright flare loops of the previously confined flare are visible in 131 Å before the flare as shown in Figure 1(c). From the AIA 304 Å image shown in Figure 1(d), we can see that the active region consists of two filaments (labeled by the green arrows F1 and F2), which only partly brighten during the flare.

2.2. Writhe of Double Hot Channels

The kinking structure of the two hot channels can be identified in 94, 131, and 193 Å, and is most obvious in 131 Å. Figure 2 shows the evolution of two hot channels with kinking structure in 131 Å, i.e., the axis of the hot channel exhibiting an “inverse γ” shape. From the top row we can see that the first hot channel becomes kinked at 18:01 UT and continues to expand. Then the kinking structure marked with orange circles gradually becomes blurred and disappears at around 18:07 UT. After the eruption of HC1, the second hot channel appears with a kinking structure at a similar location as observed in 131 Å starting from 18:14 UT. The bottom row of Figure 2 shows that the size of the kinking structure of HC2 gradually decreases with time.

As shown in Figure 1(d), two filaments can be clearly seen in this active region. The AIA image in 304 Å with a smaller field of view (FOV, marked with the yellow box) overlaid with contours of the corresponding HMI photospheric magnetic fields is plotted in the upper right corner of Figure 1(d). The footprint of filament F1 rooted in the positive polarity and the footprint of filament F2 rooted in the negative polarity are marked by green circles F1+ and F2−, respectively. When we observe the filament F1 from the positive side, its axial field points to the right. Similarly, when filament F2 is viewed from the positive side, its axial field also points to the right. Therefore, according to the definition of filament chirality
(Martin 1998), both filaments in this active region are dextral. This is consistent with the hemisphere rules, in which dextral filaments are dominant at the northern hemisphere as reported by Martin (1998). A stable filament with right-handed chirality is generally associated with left-handed writh, and its twist and crossing direction are usually negative (Török et al. 2010).

According to this theory, the kinking structure of both hot channels may correspond to negative writh, as sketched with a black curve in Figure 2. The crossing of the kinking structure of HC2 appears to be negative, which is consistent with the theory. However, it is very difficult to identify the crossing of the kinking structure of HC1 from the AIA observations (also see the online animation associated with Figure 2).

### 2.3. Apparent Footpoint Rotation of the First Hot Channel

The tricolor images in Figure 3 show the evolution of the first hot channel at three different moments. At 18:01 UT, the entire HC1 can be clearly identified in red. After the kinking, HC1 expands significantly and rises higher (green, 18:06:22 UT), then the main structure becomes blurred, and only part of the legs and footpoints can be observed (blue, 18:11:58 UT). The zoomed view of the two footpoints in 131 Å (Figures 3(b), (c)) shows that the left leg of HC1 gradually moves northeast while the right leg gradually moves southwest. The zoomed view of the footpoints in 1600 Å (Figures 3(e), (f)) shows that the left and right footpoints of HC1 are also moving together with the corresponding legs in the northeast and southwest directions, respectively. The motion of the two footpoints can also be observed in other AIA passbands, which indicates the expansion of the hot channel.

Starting from about 18:11 UT, the brightenings of both footpoints of HC1 begin to drift clockwise at the same time, which lasts about 10 minutes (marked with a yellow box in Figure 1). From the online animation of Figure 2, we can see that the drifting brightenings are connected to the first hot channel. This clockwise drifting of the brightenings at the boundary of footpoints, also called the apparent footpoint rotation, of HC1 over time is presented in Figure 4. The dashed black curves with arrows delineate the brightening trajectory. The arrows refer to the brightening front, which is connected to the legs of HC1 indicated by the orange dotted lines. The brightenings at the boundary of both footpoints of HC1 drift clockwise. The drifting of the left footpoint brightenings shown in Figure 4(b) is more prominent. The left leg of HC1 first moves westward for about 6°, and the corresponding footpoint brightenings extend and form an inverse J shape (Figure 4(b2)). Next, with the leg moving southward, the footpoint brightenings evolve into an inverse U shape (Figure 4(b3)). The brightening front rotates approximately 180° during this
process. As a comparison, the brightening front of the right footpoint of HC1 rotates approximately 120° as shown in Figure 4(c). The motion of the right footpoint starts at the corner of an L-shaped bright band (Figure 4(c1)), which first moves northward with the leg of the hot channel, and then moves westward (Figure 4(c2)). At the same time, the bright band evolves from an L shape to a J shape (Figure 4(c3)).

2.4. Footpoint Drifting of the Second Hot Channel

At 18:14 UT, about 3 minutes after the onset of the apparent footpoint rotation of HC1, HC2 appears with a blurring kinking structure near the right leg of HC1. HC1 then continues to rotate, while HC2 remains stationary. The complete structure of HC2 can be clearly identified after the disappearance of HC1. Figure 5(a) shows that the left footpoint of HC2 is located at the position where the left footpoint of HC1 stops rotating, showing a series of bright kernels. The right footpoint of HC2 is located northwest of the right footpoint of HC1, showing a group of bright kernels.

As shown in Figure 5, at 18:21 UT, the left and right footpoints of HC2 begin to move northward and westward, respectively. The northern part of the hot channel rises slightly to the north. At the left footpoint, bright kernels move from south to north in turn, and then remain stable. With the movement of the right footpoints, the original brightenings evolve into a series of bright kernels, which are connected with the right legs of HC2. As the right footpoints move westward, the kernels on the western side light up in turn, while the bright kernels on the eastern side gradually disappear. The size of the kinking structure of HC2 is shrinking during this process, and HC2 becomes more and more blurred.

The right footpoint of HC2 is slipping along a path marked by the pink broken line S in Figure 5(a), and the corresponding time–distance plot is shown in Figure 5(e). The slipping of the right footpoint of HC2 can be divided into three stages. At about 18:21 UT, it starts to slip at a speed of \( \sim 28 \text{ km s}^{-1} \). Then it quickly passes the turning point of S and continues to slip westward at a speed of \( 240 \text{ km s}^{-1} \), and slows down to \( 5 \text{ km s}^{-1} \) at the end of the slipping. Later on, another flare ribbon appears and propagates along the pink line S as reported by Jing et al. (2017). The propagation speed of this flare ribbon is \( 4-6 \text{ km s}^{-1} \) at the beginning and end, between which is \( 23 \text{ km s}^{-1} \), and is about one-tenth of the slipping speed of the footpoint of HC2.

Figure 2. Writhing evolution of the two hot channels. The top and bottom rows show AIA images of HC1 and HC2 at three different times, respectively. The orange dashed circles enclose the observed writhing structure, and the hand-drawn black curves mark the crossing direction of the two hot channels, both of which are negative crossing. An animation of this figure is available. It covers 50 minutes of observing beginning at 17:50 UT on 2015 June 22. The video duration is 12 s. The pink arrows in the movie indicate where the apparent rotations occur.

(An animation of this figure is available.)
3. Magnetic Field Modeling

In order to understand the apparent footpoint rotation of the two hot channels, we carry out a magnetic topological analysis based on the NLFFF extrapolations by Awasthi et al. (2018). The extrapolation is performed with a box of $846 \times 452 \times 452$ grids, and the FOV is marked with a white rectangle in Figure 1(b). The coronal magnetic field is extrapolated using the NLFFF code proposed by Wiegelmann (2004). The photospheric vector magnetogram closest to the moment of apparent footpoint rotation is "preprocessed" to best suit the force-free condition and then used as the boundary condition.

As mentioned in Section 1, magnetic reconnection prefers to occur at the QSLs, which can be quantified by the high squashing factor $Q$ (Titov et al. 2002), and the high-$Q$ tracers outline the footpoints of the QSLs. In order to understand the observed motion of the footpoint brightenings, we calculate the squashing factor of the extrapolated NLFFF, using the method proposed by Liu et al. (2016). Figure 6 shows zoomed AIA views of the left (left column) and right footpoints (middle column) of HC1 and the right footpoint of HC2 (right column) in 304 Å overlaid with contours of HMI photospheric magnetic fields (top row) and photospheric squashing factor log $Q$ (bottom row). The magnetic field distribution of the left footpoint of HC1 is continuous on the left side, but there is a gap in the middle and discontinuous on the right side (Figure 6(a)), while the corresponding log $Q$ is high and continuous (Figure 6(b)). A comparison of Figures 4 and 6(b) shows that the brightenings of the left footpoint drift along the high-$Q$ region. The right footpoint corresponds to a few small scattered negative magnetic polarities. A gap also exists in the corresponding log $Q$ distribution. There is a small displacement between the right footpoint brightenings of HC1 and the distribution of the high-$Q$ as shown in Figure 6(d). The brightenings of the right footpoint mainly move northward along the left side of the high-$Q$ region, and then move toward the west. In summary, brightenings of both footpoints of HC1 roughly drift along the photospheric high-$Q$ region, which results in the apparent clockwise rotation.

Compared with HC1, HC2 has a better correspondence with the distribution of photospheric magnetic fields as shown in Figure 6(e). Figure 6(f) shows that the footpoint brightenings of HC2 are situated in a high-$Q$ channel, and the footpoint is approximately slipping along the upper boundary of the high-$Q$ channel. At a similar location, another flare ribbon reported by Jing et al. (2017) brightens at about 18:40 UT in the decay phase and propagates along the high-$Q$ channel to its western end, then the corresponding coronal loops undergo apparent slipping motion following the same path of this flare ribbon.

Figure 3. Evolution of HC1. (a) and (d) AIA images observed in 131 Å and 1600 Å at three different times, displayed in red (18:01 UT), green (18:06 UT), and blue (18:11 UT), respectively. The two gray boxes in panel (a) represent the field of view of panels (b) and (c), and the two gray boxes in panel (d) represent the field of view of panels (e) and (f). Panels (b), (e) and panels (c), (f) show the zoomed view of the left and right footpoints respectively.
And the propagation path of this ribbon coincides well with the prominent QSL footpoints supporting the slipping-type reconnection. Both the slipping path of the footpoint brightenings of HC2 and the propagation path of this flare ribbon coincides well with the prominent QSL footpoints at the same location, which supports the slipping-type reconnection as interpreted by Jing et al. (2017).

4. Summary and Discussions

We investigate the footpoint motion of an M6.5 class flare that occurred in NOAA AR 12371 on 2015 June 22. AIA observes the eruption of two hot channels, both of which show kinking structures during the eruption. Previous studies show that the kinking of hot channels is often observed in the
precursor or ascending phases of the flare (Zhang et al. 2012; Cheng et al. 2013; Chen et al. 2019). However, in the flare we studied, the kinking of the two hot channels appears during the flare’s main phase. After the flare onset, the first hot channel rises up and displays a kinking structure during the ascent. As it continues to expand, the brightenings at the footpoint boundary begin to drift clockwise at the same time. The two footpoints of the second hot channel also drift, especially the right footpoint exhibits significant slipping motion.

Drifting of flux rope footpoints has been investigated in both observations and MHD simulations. Aulanier & Dudík (2019) investigates the distribution of QSLs and relevant field lines in an MHD simulation of a torus-unstable flux rope and finds that magnetic reconnection between the erupting flux rope and the inclined arcades ("ar-fr" reconnection) can result in the drifting of the flux rope footpoints. The flux rope is rooted in the hooks of the QSL, and the shift in position can also lead to the gradual drifting of the flux rope footpoints. Observational analysis of an M1.7 flare by Chen et al. (2019) shows that the bright kernels at the footpoint of the hot channel are moving along the flare ribbon hooks, which may be caused by the “ar-fr” reconnection between the hot channel and the surrounding inclined arcade. Similar to previous studies, the footpoint motion of the two hot channels in our study is also a kind of drifting motion. A combination of observational and topological analysis suggests that the drifting motion of the footpoints of the second hot channel is likely caused by the slipping reconnection between the hot channel and the surrounding magnetic fields during its unwrithing.

In order to understand the apparent footpoint rotation of the first hot channel in our event, a comparison of the observed flare ribbons and a sketch is presented in Figure 7. The two J-shaped yellow curves represent the flare ribbons (straight part) with hooks (curved part), and the blue curve represents the trajectory of the observed apparent footpoint rotation. The chirality of the filament in this active region is right-handed (dextral), and the hot channel displays an inverse S structure. A combination of the observed filament chirality and theory suggests that the kinking structure of the first hot channel likely corresponds to a negative writhe. For a flux rope with negative writhe, the clockwise rotation of its legs corresponds to the unwrithing of the flux rope, as shown in Figures 8(a)–(d) (also see the movie corresponding to Figure 8). In addition, Figure 4 shows that the brightening boundary of the flux rope’s feet gradually becomes closed, which indicates that the twist of the flux rope increases (Démoulin et al. 1996; Janvier et al. 2014; Wang et al. 2017), and since the linking number \( L = T_w + W_r \) is a topological invariant, the twist \( T_w \) increases and the writhe \( W_r \) decreases, supporting that the flux rope is undergoing the unwrithing process. In the process of unwrithing, the hot channel continues to expand, and its legs rotate while reconnecting with the surrounding magnetic fields at the high-Q region. This likely contributes to the clockwise brightening at the footpoints of the first hot channel, which is manifested as the apparent clockwise footpoint rotation of the first hot channel. The drifting motion reported by Chen et al. (2019) occurs along the flare ribbon hooks, which should display counterclockwise rotation in our case. However, the apparent clockwise rotation of the footpoint of the first hot channel in our event occurs after passing through the hook (blue curve). The footpoint brightenings in our event and the event reported by Wang et al. (2017) are both moving away.
from the flare ribbon and not along the hook. However, the apparent clockwise rotation of the footpoint brightenings in our event occurs during the eruption of the magnetic flux rope, which is different from the brightening extension in the event reported by Wang et al. (2017) corresponding to the formation process of the flux rope.

In summary, we have discovered the eruption of two kinking hot channels one after another during an M6.5 class flare (SOL2015-06-22T18:23). In this paper, we focus on analyzing the writhe of the two hot channels and the movement of their footpoints. The buildup process of these two hot channels will be discussed in the next article. The new findings in this study include: (1) The brightenings at the footpoint boundary of the first hot channel rotate clockwise after passing through the hook during the unwrithing phase. (2) The unwrithing of the second hot channel is associated with a prominent slipping motion of the right footpoint. (3) Both the apparent rotation and the slipping motion of the footpoint brightenings are likely caused by magnetic reconnection between the hot channels and surrounding fields at the high-Q region during the unwrithing of the hot channels.

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**References**

Alexander, D., Liu, R., & Gilbert, H. R. 2006, *ApJ*, 653, 719
Antiochos, S. K., DeVore, C. R., & Klimchuk, J. A. 1999, *ApJ*, 510, 485
Aulanier, G., & Dudík, J. 2019, *A&A*, 621, A72
Aulanier, G., Janvier, M., & Schmieder, B. 2012, *A&A*, 543, A110
Awasthi, A. K., Liu, R., Wang, H., Wang, Y., & Shen, C. 2018, *ApJ*, 857, 124
Baty, H. 2001, *A&A*, 367, 321
Bobra, M. G., Sun, X., Hoeksema, J. T., et al. 2014, *SoPh*, 289, 3549
Carmichael, H. 1964, in *The Physics of Solar Flares*, Proceedings of the AAS-NASA Symp. 50, ed. W. N. Hess (Washington, DC: NASA Special Publication), 451
Chen, H., Yang, J., Ji, K., & Duan, Y. 2019, *ApJ*, 887, 118
Cheng, X., & Ding, M. D. 2016, *ApJS*, 225, 16
Cheng, X., Ding, M. D., Zhang, J., et al. 2014, *ApJL*, 789, L35
Cheng, X., Zhang, J., Ding, M. D., Liu, Y., & Poomvises, W. 2013, *ApJ*, 763, 43
Demoulin, P., Henoux, J. C., Priest, E. R., & Mandrini, C. H. 1996, *A&A*, 308, 643
Démoulin, P., Priest, E. R., & Lonie, D. P. 1996, *JGR*, 101, 7631
Fan, Y. 2005, *ApJ*, 630, 543
Fan, Y., & Gibson, S. E. 2003, *ApJL*, 589, L105
Fan, Y., & Gibson, S. E. 2004, *ApJ*, 609, 1123
Fan, Y., & Gibson, S. E. 2007, *ApJ*, 668, 1232
Gibson, S. E., & Fan, Y. 2006, *ApJL*, 637, L65
Gilbert, H. R., Alexander, D., & Liu, R. 2007, *SoPh*, 245, 287
Green, L. M., Kliem, B., & Wallace, A. J. 2011, *A&A*, 526, A2
Hirayama, T. 1974, *SoPh*, 34, 323
Hou, Y. J., Zhang, J., Li, T., Yang, S. H., & Li, X. H. 2018, *A&A*, 619, A100
Janvier, M., Aulanier, G., Bommier, V., et al. 2014, *ApJ*, 788, 60