Evolution of a Magnetic Flux Rope toward Eruption

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Abstract

It is well accepted that a magnetic flux rope (MFR) is a critical component of many coronal mass ejections (CMEs), yet how it evolves toward eruption remains unclear. Here we investigate the continuous evolution of a pre-existing MFR, which is rooted in strong photospheric magnetic fields and electric currents. The evolution of the MFR is observed by the Solar Terrestrial Relations Observatory (STEREO) and the Solar Dynamics Observatory (SDO) from multiple viewpoints. From STEREO’s perspective, the MFR starts to rise slowly above the limb five hours before it erupts as a halo CME on 2012 June 14. In SDO observations, conjugate dimmings develop on the disk, simultaneously with the gradual expansion of the MFR, suggesting that the dimmings map the MFR’s feet. The evolution comprises a two-stage gradual expansion followed by another stage of rapid acceleration/eruption. Quantitative measurements indicate that magnetic twist of the MFR increases from 1.0 $\pm$ 0.5 to 2.0 $\pm$ 0.5 turns during the five-hour expansion, and further increases to about 4.0 turns per astronomical unit when detected as a magnetic cloud at 1 au two days later. In addition, each stage is preceded by flare(s), implying reconnection is actively involved in the evolution and eruption of the MFR. The implications of these measurements on the CME initiation mechanisms are discussed.

Key words: Sun: coronal mass ejections (CMEs) – Sun: flares – Sun: magnetic fields

Supporting material: animations

1. Introduction

In situ measurements of many coronal mass ejections (CMEs) near the Earth reveal a magnetic flux rope (MFR) structure, which possesses helical magnetic fields. These interplanetary CMEs are sometimes called magnetic clouds (MCs; Burlaga et al. 1981, 1982), a dominant contributor to adverse space weather when they are directed toward the Earth. Now it is generally accepted that MFRs originate from the Sun (Gosling 1990). Therefore, it is of critical importance to understand how an MFR forms and evolves on the Sun, and what mechanism triggers its eruption.

Although it is believed that an MFR can form on the Sun, it is not clear when and how it forms. MFRs may emerge from the photosphere (e.g., Fan & Gibson 2004; Fan 2009), or form by magnetic reconnection (e.g., van Ballegooijen & Martens 1989). They can stay in equilibrium in the corona until eruption, and thus are called pre-existing MFRs. Observations in the past decades have provided evidences for pre-existing MFRs. Forward or reversed S-shaped sigmoids in soft X-rays or EUV images are sometimes observed hours before the eruption, and are often considered as a manifestation of the MFR topology (Rust & Kumar 1996; Aurass et al. 2000; Green et al. 2007, 2011; Liu et al. 2010b; Savcheva et al. 2014). Filaments or prominences are thought to be plasma identities of MFRs (Vršnak et al. 1988, 1991; Low & Hundhausen 1995; Dere et al. 1999; Liu et al. 2012a). Recent studies suggest that, for a prominence-cavity system, the cavity can be considered as a pre-existing MFR with prominence material embedded at the bottom of the flux rope (see the details in a review by Schnieder et al. 2015). Lately, the so-called hot blob (Cheng et al. 2011), which appears bright in high-temperature passbands ($T \geq 8$ MK) but is observed as a dark cavity in other low-temperature passbands, is also interpreted as an MFR (e.g., Zhang et al. 2012; Song et al. 2014; Nindos et al. 2015). Gradual development of pre-eruption dimmings is considered as another signature for the existence of a pre-existing MFR (Gopalswamy et al. 1999; Qiu & Cheng 2017).

The eruption of a pre-existing MFR may be triggered by an ideal MHD instability, such as torus instability (Bateman 1978; Kliem & Török 2006) or kink instability (e.g., Dungey & Loughhead 1954; Hood & Priest 1979; Török & Kliem 2005). Torus instability may occur when the downward Lorentz force exerted upon the MFR by the envelope field $B_p$ decreases more steeply with height $h$ than the hoop force of the MFR current (Kliem & Török 2006), i.e., when the decay index ($n = -d \ln B_p/d \ln h$) exceeds a critical value $n_{\text{crit}}$. Analytical and numerical MHD models suggest this critical value falls in the range of 1–2, depending on magnetic configurations (Fan & Gibson 2007; Aulanier et al. 2010; Démoulin & Aulanier 2010; Zuccarello et al. 2016). For example, Bateman (1978) and Kliem & Török (2006) derived $n_{\text{crit}}$ of 1.5 for an idealized current ring. In MHD simulations, $n_{\text{crit}}$ is found to be in the range of 1.4–2.0 (Fan & Gibson 2007; Zuccarello et al. 2016). Also, an MFR may become kink-unstable when it acquires a sufficient amount of twist, i.e., the number of turns that the magnetic field lines wind around the rope axis. Theoretical and numerical studies have estimated the critical twist $T_{\text{crit}}$ in flux ropes with different magnetic configurations (Dungey & Loughhead 1954; Hood & Priest 1979; Bennett et al. 1999; Baty 2001; Török et al. 2004; Fan 2005; Török & Kliem 2005; Kliem et al. 2010). For example, Hood & Priest (1981) derived $T_{\text{crit}}$ of 1.25 turns in a nonlinear force-free MFR with the uniform-twist solution (Gold & Hoyle 1960). Fan & Gibson (2004) found that a line-tied flux tube that emerged into a
coronal potential field erupted when its twist reached 1.76 turns. Török et al. (2004) provided $T_{\text{crit}} \approx 1.75$ turns in a force-free coronal loop model (Titov & Démoulin 1999). In a magnetostatic configuration ($\beta = 0$), the profile of pressure gradient and plasma compressibility also affect the stability (Newcomb 1960; Hood & Priest 1979; Einaudi & Van Hoven 1983).

The eruption of an MFR can also be triggered by magnetic reconnection. The main role of reconnection is to remove the field lines originally confining the MFR and thus to release it. Reconnection may occur below an MFR (Forbes & Priest 1984, 1995; Forbes 1990; Chen & Shibata 2000; Moore et al. 2001), above an MFR (e.g., Antiochos et al. 1999), or within a compound MFR system (e.g., Liu et al. 2012a; Zhu et al. 2015; Awasthi et al. 2018).

On the other hand, a coherent MFR structure might not be present prior to its eruption, but is created by magnetic reconnection, i.e., in situ formed. For example, reconnection may occur between neighboring sets of field lines in a sheared magnetic arcade, resulting in a flux rope (e.g., Mikic et al. 1988; Mikic & Linker 1994; Démoulin et al. 1996, 2002). Wang et al. (2017) identified two newly formed and expanding bright rings enclosing conjugate dimming regions, suggesting the dynamic formation of an MFR via reconnection. Guo et al. (2018) observed that a leading plasmoid formed at the upper tip of a pre-existent current sheet through the coalescence of plasmoids, and then expanded impulsively into a CME bubble. During the eruption, reconnection could add a significant amount of magnetic flux into an MFR (Lin et al. 2004), as implied by a statistical comparison between the flux budget of interplanetary MCs and the reconnection flux in their source regions (Qiu et al. 2007; Hu et al. 2014).

To help understand mechanisms for the formation and eruption of MFRs, it is important to measure the magnetic properties of MFRs. However, direct measurement of the coronal magnetic fields is still unavailable, thus it poses a major challenge to the observational investigation of the MFR properties. An alternative approach is to investigate the footpoints of MFRs that are anchored to the Sun (e.g., Qiu et al. 2007; Wang et al. 2017). In this study, combining remote-sensing observations and in situ detection, we identify a pre-existing MFR, and quantify its magnetic and dynamic properties during five hours before its eruption. Both feet of the MFR are cospatial with strong magnetic fields and electric currents. This unique event allows us to test the roles of reconnection and/or ideal MHD instabilities played in the evolution of the MFR. In the following text, Section 2 highlights key observations. Section 3 describes the methods used to identify the feet of the MFR. Then we analyze quantitative measurements and evolution of the MFR in Section 4. Discussions and conclusions are given in Section 5.

2. Overview of Observations

The eruption of interest occurred in a sigmoidal active region (AR 11504) on 2012 June 14, which was observed by the Solar Dynamics Observatory (SDO; Pesnell et al. 2011) and the Solar Terrestrial Relations Observatory (STEREO; Kaiser et al. 2008). The host active region is characterized by fast sunspot rotation with an average speed of 5° hr$^{-1}$, exceeding the typical speed of 1°–2° hr$^{-1}$ (Zhu et al. 2012), and shear flows lasting for a few days. It produced several confined flares and an eruptive M1.9 flare (Figure 1(a)) on 2012 June 14. From SDO’s perspective, the active region was located near the disk center (S17W00). The Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board SDO takes full-disk images up to 1.5 $R_S$ at a spatial scale of 0′6 pixel$^{-1}$ in seven EUV channels with a cadence of 12 s and two UV channels with a cadence of 24 s spanning a broad range of temperature. In this paper, we mainly used 1600 Å (CIV + continuum; log $T = 5.0$, 3.7), 304 Å (He II; log $T = 4.7$), and 94 Å (Fe XVIII; log $T = 6.9$) channels to study flare ribbons, coronal dimmings, and flare loops, respectively. The STEREO “Ahead” and “Behind” spacecraft (hereafter STA and STB) captured the eruption at its east and west limbs on that day, respectively. Images taken by the Extreme Ultraviolet Imager (EUVI; Howard et al. 2008) on board STB in 195 passband with a 5 minute cadence reveal a gradual expansion of a coronal structure (see Figure 2) lasting for more than five hours before the eruption. The slowly expanding coronal structure finally evolved into a halo CME propagating at about 1000 km s$^{-1}$ when observed in white light by COR2 coronagraph on board STEREO (Figures 1(b) and (c)). The image from STA/COR2 (Figure 1(b)) shows the CME with clear helical features. Two days later, it passed through WIND spacecraft at 1 au and was identified as an MC (James et al. 2017; Palmiero et al. 2017), indicating that an MFR is involved in the eruption.

Coronal dimmings are observed in two regions with opposite magnetic polarities (Figure 1(a)). The twin dimming regions (in 304 Å) near the two ends of the S-shaped sigmoid (in 131 Å) are labeled as “conjugate dimmings.” To study their evolutions, time–distance maps along two slits (Figure 1(a)) through the dimming regions are generated, as shown in Figure 3. These maps demonstrate that the dimmings have started five hours before the eruption. The pre-eruption dimmings, as indicated by the normalized light curves of two dimming segments (Cut1 and Cut2 in Figures 3(c1) and (d1), respectively), are clearly visible in almost all AIA channels (except 94 Å in the western dimming region, see Figures 3(a) and (b)), implying that the changes in the brightnesses are primarily due to a decrease in plasma density rather than a change in temperature. In addition, conjugate dimmings evolve simultaneously with the expanding coronal structure, suggesting that the dimmings map the feet of the coronal structure. It is noteworthy that the conjugate dimmings in this event are cospatial with strong magnetic fields and vertical electric currents (Figures 1(d) and (e)) measured with vector magnetograms obtained by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012). These observations indicate that the coronal structure is associated with a pre-existing MFR, and allow us to quantify its magnetic properties and study its evolution in detail, as presented below.

3. Identification of the MFR’s Feet

Similar to some previous studies (Webb et al. 2000; Qiu et al. 2007; Cheng & Qiu 2016; Wang et al. 2017), we utilize conjugate dimmings to identify the MFR’s feet. Many studies suggest that observations in chromospheric/transition-region lines are less subject to coronal loop projection, compared with those in coronal lines (Harvey & Recely 2002; Harra et al. 2007; Qiu et al. 2007; Scholl & Habbal 2008). We hence detect dimmings in the AIA 304 images at a cadence of 1 minute, starting from 07:00 to 18:00 UT. All AIA images are differentially rotated to the same moment (two hours before the M1.9 flare) using the standard SolarSoftware packages.
For each image, we select dimmed pixels within two regions at ends of the sigmoid by a thresholding method: a pixel is flagged when its brightness is reduced by 30% compared with its original value averaged between 07:00 and 08:00 UT, and displays continuous decline until eruption. The two contours in Figures 1(d) and (e) enclose all the identified dimming pixels. We thus consider the two contours (“FP+” and “FP−”) encompass maximum areas of the MFR’s conjugate footpoints in the positive and negative fields, respectively.

The magnetic properties at the feet of the MFR are studied by projecting the identified dimming pixels onto HMI vector magnetograms. The magnetogram is disambiguated and deprojected to the heliographic coordinates with a Lambert cylindrical equal area projection method, resulting in a pixel scale of 0.36 Mm (Bobra et al. 2014). The magnetic fluxes (Φz in Table 1) are calculated in two conjugate footpoints. In order to avoid the effect of noise in the HMI magnetogram, only the vertical magnetic fields with the strengths |Bz| > 20 G (Liu et al. 2012b; Hoeksema et al. 2014) are used. It is also noted that in each footpoint, the magnetic flux of one polarity over-dominates the other polarity by more than two orders of magnitude; therefore, each footpoint can be treated as monopolar. In addition, we calculate the vertical current density $J_z = (\nabla \times B_z)/\mu_0$ ($\mu_0 = 4\pi \times 10^{-7}$ H m$^{-1}$) (Figure 1(e)) in the vector magnetogram mentioned before. All measurements are listed in Table 1 and will be discussed in detail in the next section.

4. Properties and Evolution of the MFR

In the following sections, we investigate the evolution of the conjugate dimmings and the expanding coronal structure in detail, showing how the MFR evolves toward the eruption. Then we analyze the results of measurements and infer magnetic twist of the MFR during that period. In addition, we found obvious temporal and spatial relationships between flares and the evolution of the MFR.

4.1. Dynamic Evolution

To show the dimming evolution, we plot the light curve of the average brightnesses ($I_{FP+}$ and $I_{FP−}$) for the two fixed regions (“FP+” and “FP−” in Figure 1(d)) respectively, as seen in Figure 4(b). The dimmings go through three stages (marked in Figure 4(b)). During the first stage, both $I_{FP+}$ and $I_{FP−}$ increase almost simultaneously and gradually for about three hours. While in the second stage, $I_{FP+}$ and $I_{FP−}$ decrease more rapidly than in the previous one. About two hours later, $I_{FP+}$ reaches its minimum, which is 75% of its brightness at 08:00 UT. At 13:25 UT, $I_{FP−}$ reaches its minimum, which is 65% of its brightness at 08:00 UT. After that, both $I_{FP+}$ and $I_{FP−}$ start to increase, corresponding to the third stage.

Dimming is usually related to reduced plasma density associated with an expanding coronal structure (e.g., Harrison & Lyons 2000; Harra & Sterling 2001). STB/EUVI 195 Å images indeed reveal the slow rise of a coronal structure, which persists for five hours before the eruption. The evolution of this structure is outlined by
red dashed lines in Figures 2(a1)–(f1). To track its motion, a time–distance stack plot along a fixed slit of “s1” (Figure 2(a2)) is generated. The red dashed lines in Figure 4(c) indicate linear fittings of its trajectory along the slit at three stages coincident with those of the dimming evolution. It is notable that, from the first to the second stage, as the coronal structure expands more rapidly, the brightness in dimming regions also decreases more quickly.

The expanding coronal structure finally erupts as a halo CME (Figures 1(b) and (c)), which arrives at Earth two days later and is identified as an MC with strong magnetic fields peaking at ~40 nT (James et al. 2017; Palmerio et al. 2017). We employ the Grad–Shafranov reconstruction method (Hu & Sonnerup 2002; Qiu et al. 2007; Hu et al. 2014) to derive the magnetic structure of the MC. The result suggests that it is a highly twisted flux rope with 4.0 turns per astronomical unit (au). In summary, the combined remote-sensing image and the in situ detection support the existence of a pre-existing MFR that roots in the conjugate dimming regions.

4.2. Magnetic Properties

We infer the magnetic properties of the MFR from its feet (FP+ and FP− in Figure 1(d)). Table 1 lists the measurements at the two feet, including the mean vertical magnetic field \( \langle B_r \rangle \), mean transverse field \( \langle B_\theta \rangle \), total magnetic flux \( \Phi_\Omega \), mean vertical current density \( \langle J_z \rangle \), and total current \( I \). The FP+ is inside the leading sunspot with \( \langle B_r \rangle \approx 1500 \) G, magnetic flux \( \Phi_\Omega \approx 4.2 \times 10^{21} \) Mx. In FP+, the positive current \( I_+ \approx 1.7 \times 10^{12} \) A dominates over the negative current \( I_- \approx -0.5 \times 10^{12} \) A, resulting in a net positive current \( I_{\text{net}} \approx 1.3 \times 10^{12} \) A. The FP− is located within a so-called magnetic tongue (Luoni et al. 2011) near the polarity inversion line (PIL), with \( \langle B_r \rangle \approx -700 \) G, and \( \Phi_\Omega \approx -3.0 \times 10^{21} \) Mx. In FP−, the negative current \( I_- \approx -3.8 \times 10^{12} \) A is about twice the positive current \( I_+ \approx 2.0 \times 10^{12} \) A. As a result, FP− has a net negative current \( I_{\text{net}} \approx -1.8 \times 10^{12} \) A. Thus both \( \Phi_\Omega \) and \( I \) at the two feet are comparable and of opposite signs, agreeing with the scenario that the conjugate dimming regions are connected by a current-carrying MFR.

Based on the observational measurements listed in Table 1, the magnetic twist \( T \) of the MFR can be estimated with three methods. First, under a simplified assumption of an axial-symmetric cylindrical flux rope, the twist is given by

\[
T = \frac{LB_z(r)}{2\pi rB_r(r)}
\]

in cylindrical coordinates \( (r, \theta, z) \), where \( L \) is the length of the MFR axis, and \( r \) is the distance to the axis. The twist per unit length at each foot, \( \tau = T/L \), is calculated utilizing the
photospheric magnetogram. We treat the geometric center of each foot as the axis of the MFR; $r$ is the distance of a pixel to the center (or axis), and $B_{\theta}$ is calculated from the transverse field $B_t$. We hence obtain $\tau$ for every pixel in FP+ and FP−. We then shift the center by up to a quarter of the foot size, and find that the uncertainty is about $1.2 \times 10^{-3}$ turns Mm$^{-1}$. Then the total twist along the MFR is evaluated with the averaged value $\langle \tau \rangle$ by $T = \langle \tau \rangle L$. $L$ is determined by assuming a circular-arc shape of the MFR, utilizing the height of the coronal structure and the distance between two geometric centers of its feet. We derived the errors of $B_z$ and $B_t$ from the uncertainties of HMI data (Liu et al. 2012b; Hoeksema et al. 2014) and found that the errors vary within 20 Gauss for $B_z$ and 100 Gauss for $B_t$ during the five-hour evolution.

We hence calculate the twist using the effective pixels that satisfy two conditions ($B_t > 100$ G and $B_z > 20$ G). The time variation of $\langle \tau \rangle$ and $T$ in each region is plotted in Figure 5(a).

The second and third methods both assume nonlinear force-free magnetic configuration (Liu et al. 2016). The twist of a field line about its own axis (rather than the axis of an imaginary cylinder) is given by (Berger & Prior 2006)

$$T = \int_0^L \frac{\mu_0 d}{4\pi B} dl,$$

Figure 3. Pre-eruption dimmings observed in seven AIA EUV channels. Panels (a) and (b) show the normalized light curves of the dimmed segments of Cut1 in (c1) and Cut2 in (d1) for seven AIA channels, respectively. Panels (c) and (d) at the bottom are time–distance maps along the two slits (Figure 1(a)) from 304, 211, and 131 Å base-difference images. “Slit_east” starts from its western endpoint (c1–c3). “Slit_west” starts from its eastern endpoint (d1–d3). The darker regions, marked by arrows, indicate the pre-eruption dimmings. Green vertical lines represent the start time of the M1.9 flare.
Under the nonlinear force-free assumption, \( J / B \) is constant along the same field line and is equal to \( J / B \) at its feet, though varies across different field lines. Thus Equation (2) gives \( \tau = (\mu_0 J)/(4\pi B) \). We take the average value (\( \tau \)) over all pixels in FP+ and FP−, respectively. Figure 5(b) shows the evolution of (\( \tau \)) and \( T \). The third method is similar to the second one; instead of measuring \( \tau \) at each pixel and taking the average over all pixels, we measure

\[
T = \frac{\mu_0 I}{4\pi \Phi} L
\]

where \( I \) is the current and \( \Phi \) is the total magnetic flux in each foot. The results from this method are plotted in Figure 5(c).

Without knowing the exact configuration of the MFR, we regard that the measurements with the above three methods provide a possible range of twist in the MFR. Figure 5 shows that the twists estimated by these methods exhibit similar behavior in general. Based on the three methods, the original value of \( T \) is \( 1.7 \pm 0.4, \ 0.9 \pm 0.5, \) or \( 0.6 \pm 0.3 \) turns, respectively, and it then increases to \( 2.8 \pm 0.4, \ 1.6 \pm 0.6, \) or \( 1.6 \pm 0.2 \) turns correspondingly before the eruption. Despite discrepancies in exact values, all three methods suggest that the total twist \( T \) of the MFR has increased by about 1.0 turn during the pre-eruption phase.

The magnetic helicity inside the MFR can be estimated by \( H = T \Phi^2 \) (Berger & Field 1984; Webb et al. 2010), where \( T \) is the total twist and \( \Phi \) is toroidal flux calculated by the effective pixels. The \( \langle H \rangle \), averaged over the measurements, gradually increases from \( 6.0 \pm 3.8 \) to \( 10.4 \pm 2.0 \times 10^{12} \) Mx² during the pre-eruption phase. To make a comparison, we also investigate the relative helicity of the host active region. We calculated the helicity injection across the photospheric boundary \( S \) of the active region using the following formula:

\[
\frac{dH}{dt} |_{t} = 2 \int_{S} (A_{p} \cdot B_{z}) V_{1,n} dS - 2 \int_{S} (A_{p} \cdot V_{1}) B_{n} dS,
\]

where \( A_{p} \) is the vector potential of the reference potential field; \( t \) and \( n \) refer to the tangential and normal directions, respectively;
is the photospheric velocity that is perpendicular to magnetic field lines, and is composed of an emergence term \( V_{n} \) and a shear term \( V_{t} \). Readers are referred to Liu et al. (2016) and references therein for more information. The accumulated helicity calculated at the two feet of the MFR is about 1.2 \( \pm \) 0.4 \( \times 10^{42} \) Mx² during the five-hour evolution, which is translated to a twist number of about 0.2 turn. Also, the sunspot rotation could contribute a twist number up to 0.1 turn during this period.

### 4.3. Relationships between the Flares and the MFR Evolution

The pre-existing MFR undergoes three stages, indicated by its rising motion at three different speeds and the evolution of the conjugate dimmings. It is noteworthy that each stage is preceded by flare(s) (Figure 4(a)). At around 08:00 UT, two homologous C-class flares (C2.0 and C1.6, see Figures 6(c1) and (c2)) occur successively. Meanwhile, the MFR begins to rise, and the dimmings start to develop at its feet. The slow expansion of the MFR continues until another set of homologous C-class flares (C2.5 and C5.0, see Figures 6(c3) and (c4)) take place. After that, the MFR rises more rapidly, and the conjugate dimmings develop more steeply. The ribbons of these four flares (contours in Figure 6(a)) are primarily located along the edges of the MFR’s two feet. And the magnetic polarity of each ribbon is opposite to its nearby feet of the MFR, forming a quadrupole configuration.

The M1.9 flare occurs at around 12:50 UT. Different from the previous C-class flares, the ribbons of the M1.9 flare spread into the MFR’s two feet, as seen in Figures 6(d1)–(d4). Figure 6(b) shows the movement of the M1.9 flare ribbons, with a different color at a varying time. At the maximum area, the flare ribbons have encompassed almost half the areas of MFR’s feet. We measure the magnetic fluxes in the areas swept up by the newly brightened ribbons. These fluxes are equivalent to magnetic reconnection flux in the corona (Qiu et al. 2007). Figure 4(a) shows the reconnection flux and its time derivative, or the magnetic reconnection rate. It is noted that the reconnection rate grows abruptly at 13:25 UT, when the MFR is suddenly accelerated (Figure 4(c)) and then ejected.

### 5. Discussion and Conclusion

The MFR studied in this work undergoes a complex three-stage evolution. It is of interest to determine the physical mechanism(s) behind the MFR evolution. In the following sections, we first discuss the possible initiation mechanisms, including ideal MHD instabilities and magnetic reconnection.
We then focus on evolution of the host active region to discuss the formation of the MFR.

5.1. Ideal MHD Instabilities

Observations of this event provide a unique opportunity to examine the role of ideal MHD instabilities during the evolution of the MFR, such as kink and torus instabilities. In Figure 7, we show the total twist of the MFR measured with three methods. During these five hours, the MFR can be considered to be evolving in quasi-equilibrium. Theoretical and numerical studies have estimated $T_{\text{crit}}$ for kink instability to be somewhere between 1.0 and 2.0 turns, depending on the specific configuration of MFRs (e.g., Dungey & Loughhead 1954; Hood & Priest 1979; Bennett et al. 1999; Baty 2001).

The quasi-equilibrium evolutions suggest that the kink instability might not occur during the pre-eruption phase, though the twist of the MFR may have exceeded $T_{\text{crit}}$ from some previous studies. Our measurements provide the value of $T_{\text{crit}}$ as 2.0 ± 0.5 turns, if the final eruption is triggered by kink instability.

To examine the possible role of the torus instability, we measure the decay index $n$ of the envelope magnetic field $B_p$ at the height of the MFR as it rises. We use the PFSS package in SolarSoftware, which takes into account the full sphere by assimilating magnetograms into a flux dispersal model (Schrijver & DeRosa 2003), and yields the coronal fields with a potential-field source-surface model at 12:04 UT. Figure 7(b) displays $B_p$ above the PIL at the CME's varying heights. As the MFR rises from 25 to 50 Mm in the first stage, $B_p$ decreases from 100 to 50 G, and the decay index increases from 1.0 to 1.5. In the next two hours, the MFR rises to 100 Mm at the onset of the eruption, while $B_p$ keeps decreasing to nearly 20 G, and the decay index has reached 1.9. Therefore, if torus instability triggers the MFR eruption, the decay index threshold would be $\sim 1.9$ in this study, corresponding to the critical values of 1.1–2.0 from previous works (e.g., Fan & Gibson 2007; Démoulin & Aulanier 2010; Zuccarello et al. 2016).

5.2. Roles of the Reconnection

The observations of a series of flares indicate that reconnection may play important roles in the MFR evolution. The four C-class flares, with the ribbons located adjacent to the MFR’s feet, probably help to reduce the constraints from the envelope fields, resulting in the continuous rising of the MFR. On the other hand, our measurements suggest the twist of the MFR increases by about 1.0 turn during its quasi-static evolution. The photosphere evolution can contribute to a twist number of 0.2 turn into the MFR, implying that most of the increased twist may come from reconnection in the corona.
This is reminiscent of numerical simulations by Fan (2010), which demonstrate that tether-cutting reconnections can add twisted flux to the MFR, allowing it to rise quasi-statically to the critical height of torus instability. We note that James et al. (2017) studied this event and concluded the MFR formed via tether-cutting reconnection, two hours before the eruption. Tether-cutting reconnection can indeed convert sheared flux into the MFR. However, our analysis of SDO and STEREO observations suggest that the MFR, or at least its seed, was present at least five hours before the eruption, considering the synchronous evolution of the conjugate dimmings and the coronal structure, as well as the strong currents at its two feet. The rapid acceleration of the MFR occurs in the impulsive phase of the M1.9 flare, similar to previous studies (Zhang et al. 2001; Cheng et al. 2003; Gallagher et al. 2003; Qiu et al. 2004; Zhang & Dere 2006; Gopalswamy et al. 2012). Noteworthily, the geometry of the M1.9 is quite different from the earlier C-class flares. The flare ribbons, which map the footpoints of newly formed loops via reconnection, spread into the two feet of the MFR, indicating that reconnection takes place between the two legs of the MFR (e.g., leg–leg reconnection, Kliem et al. 2010).

5.3. Evolution of the Host Active Region

Strongly non-neutralized currents in an active region may be an essential condition for eruptions. Recently, Liu et al. (2017) found that the production of CMEs is related to the neutralization of the electric current in the host active region. They calculated the ratio of direct and return currents, and found it ranged from 2.0 to 3.0 in two active regions with CMEs, while it was about 1.0 for the other two active regions without CMEs. For this event, however, the ratio is about 1.0 in this active region with the CME, but at both feet of the MFR is about 2.9 (3.8 for FP+, 1.9 for FP–), suggesting the MFR carrying strong current may be essential for the eruption. To prove that, statistical studies are required in the future.

Meanwhile, the formation of an MFR in the corona is thought to be associated with evolution of its host active region, i.e., the injections of magnetic energy and helicity (Low 1994; Liu et al. 2010a). The MFR in this study is found to carry a strong electric current rooted in the rotating sunspot and the magnetic tongue. Thus the long evolution of AR 11504 from June 11 to 15 are investigated, including the magnetic flux, the relative helicity, and the Poynting flux, as shown in Figure 8. The Poynting flux is calculated across the photospheric boundary $S$ of the active region using the following formula (see the details in Section 2.2 and Appendix B in Liu et al. 2016)

$$\frac{dP}{dt} = \frac{1}{4\pi} \int_S B_i^2 \nu_{li,\alpha} \ dS - \frac{1}{4\pi} \int_S (\mathbf{B}_i \cdot \mathbf{V}_{li}) \mathbf{B}_\alpha \ dS. \quad (5)$$

The total flux of the active region grows until mid-day June 13. The total helicity and Poynting fluxes into the active region keep rising, characterized by the sunspot rotation and the shear.
flows in the trailing plage. During the pre-eruptive evolution, the photospheric evolution can inject a twist number of 0.2 turn into the MFR. Note that the calculation of the helicity injection and the twist of the MFR follow the different assumptions. It is difficult to conclude the role of the photospheric evolution plays in the build-up of the MFR only from the quantitative difference.

5.4. Conclusions

In this study, we analyze the evolution of the pre-eruption dimmings and an associated expanding coronal structure during five hours before its eruption into a halo CME, utilizing the triple-viewpoint observations from SDO and STEREO. Our study suggests the existence of a pre-existing MFR, with its two feet being mapped by the conjugate dimmings. The MFR undergoes a three-stage evolution, i.e., a two-stage gradual expansion followed by another rapid acceleration/eruption. Moreover, quantitative measurements indicate that magnetic twist of the MFR increases by about 1.0 turn during the two-stage gradual expansion.

The results raise two major questions for this study: what causes the MFR’s gradual expansion? how does magnetic twist increase during the expansion of the MFR? As discussed in previous sections, the four confined flares might help weaken the envelope field of the MFR, resulting in the expansion. On the other hand, magnetic reconnection may play a major role in the increase of the MFR’s twist during the five-hour evolution. Another important question is what triggers the MFR eruption. If ideal MHD instability is responsible for the eruption, our study gives the critical value of 2.0 ± 0.5 turns for kink instability and the critical decay index of 1.9 for torus instability. The MFR erupts in the impulsive phase of the M1.9 flare, implying reconnection may also trigger the eruption. During the eruption, the leg-leg reconnection may have contributed a significant amount of twist into the MFR, such that the MC possesses a high twist of 4.0 turns per au, compared with other MCs in a statistic study (Hu et al. 2014).

This study raises many other interesting questions. For example, how often can pre-eruption dimmings be observed? What are the temporal and spatial relationships between ribbons and dimmings if both are observed? How often can MFRs be found to carry strong currents? To answer these questions, further investigations are underway.

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