Magnetic Reconnection Invoked by Sweeping of the CME-driven Fast-mode Shock

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Abstract

Coronal waves exist ubiquitously in the solar atmosphere. They are important not only because of their rich physics but also because they are essential candidates for triggering remote magnetic eruptions. However, the latter mechanism has never been directly confirmed. By revisiting the successive eruptions on 2012 March 7, fast-mode shocks are identified to account for the X5.4 flare-related Extreme UltraViolet wave with a velocity of 550 km s$^{-1}$, and appeared faster than 2060 ± 270 km s$^{-1}$ at the front of the corresponding coronal mass ejection in the slow-rising phase. They not only propagated much faster than the local Alfvén speed of about 260 km s$^{-1}$, but also were simultaneously accompanied by a type II radio burst, i.e., a typical feature of a shock wave. The observations show that the shock wave disturbs the coronal loops C1 connecting active regions (ARs) 11429 and 11430, which neighbor a null point region. Following a 40 minute oscillation, an external magnetic reconnection (EMR) occurred in the null point region. About 10 minutes later, a large-scale magnetic flux rope overlaid by C1 became unstable and erupted quickly. It is thought that the fast-mode shock triggered EMR in the null point region and caused the subsequent eruptions. This scenario is directly observed for the first time, and provides new hints for understanding the physics of solar activities and eruptions.

Unified Astronomy Thesaurus concepts: Solar magnetic reconnection (1504); Solar magnetic fields (1503); Solar coronal waves (1995); Solar activity (1475); Solar flares (1496)

Supporting material: animation

1. Introduction

Coronal waves are a common physical phenomena, mostly disturbances triggered by a related impulsive energy releasing process, that exist ubiquitously in the solar corona. With improved observations, e.g., the global coverage and high time cadence of the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) aboard the Solar Dynamics Observatory (SDO; Pesnell et al. 2012), coronal waves have been increasingly understood not only regarding the aspects of the mechanisms themselves, but also the investigation of whether such large-scale traveling disturbances can trigger remote eruptions (e.g., Warmuth 2015).

Various waves invoked by the eruption in the solar atmosphere have been observed in different wavelengths and frequently reported. Among them, the extreme ultraviolet (EUV) wave has been studied most frequently due to extensive observations from the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995), the Solar Terrestrial Relations Observatory (STEREO), and, especially, SDO/AIA with high-cadence. The EUV wave is often found to have two distinct parts: a leading wave-like front, and a slower trailing front ahead of the coronal dimming area (Thompson et al. 1998; Liu & Ofman 2014). The leading front was interpreted as a fast-mode wave (e.g., Warmuth et al. 2001; Patsourakos & Vourlidas 2009; Veronig et al. 2010; Ma et al. 2011), and can propagate to the remote corona. In light (WL) images, the fast EUV wave is often colocated with the leading shock-front of the related coronal mass ejection (CME) and is followed by the sharp density enhancements of CME structure (e.g., Vourlidas et al. 2003). In a composite of the WL and the EUV images, it is not difficult to recognize whether the EUV wave is the counterpart of a WL shock in the EUV band (e.g., Tripathi & Raouafi 2007). The impulsive cavity expansion during a CME may trigger fast EUV waves, most likely due to a fast lateral expansion (Veronig et al. 2008, 2018; Patsourakos et al. 2010). A laterally propagating wavefront-like feature can be identified in STEREO/COR1 as the upper coronal counterpart of an EUV wave (e.g., Kwon et al. 2013; Hu et al. 2019). The consistent observations of the coronal wave in EUV and WL observations help us understand the physics of such a propagating disturbance in different wavelengths, especially for the events observed from the solar limb.

When determining modes of fast coronal waves related to flare/CMEs, in addition to direct observational characteristics of actual velocity, other interferometric imaging of the radio domain, such as metric type II radio bursts, is a typical criterion for identifying fast-mode shocks as well. Type II radio bursts as reported for the first time by Payne-Scott et al. (1947) and Wild & McCready (1950) appear as slowly drifting bands of emission in dynamic radio spectra. They are characteristic signatures of expanding coronal shock waves traveling outwards through the corona at speeds exceeding the local magnetoacoustic wave speed (or the local Alfvén speed in the force-free environment) (e.g., Uchida 1960). The relationship between EUV wave and type II burst has recently been investigated. Biesecker et al. (2002) checked 173 EUV waves from 1997 March through 1998 June, and found only 23% of EUV waves are accompanied by type II bursts. A consistent
association rate of 22% was obtained by Muhr et al. (2014) via analyzing 60 strong large-scale EUV wave events that occurred during 2007 January to 2011 February observed by the STEREO twin spacecraft. Gopalswamy et al. (2009) suggested that EUV waves may usually coincide with the occurrence of the metric type II burst in the early phase of eruptions. Conversely, Klassen et al. (2000) studied 21 metric type II events observed in 1997 with the Potsdam radio spectral polarimeter, and noted that 90% of metric type II bursts are associated with the EUV wave. The type II burst can therefore help identify the EUV wave with its correlated shock. However, only a fraction of the EUV waves (about 20%–25%) are indeed shock waves. The other fraction should be large-amplitude waves, but not shocks.

As a propagating disturbance triggered in the corona, it is often questioned whether coronal waves may cause an eruption in a remote region. On the one hand, we often observe that a preceding flare triggers a distant sympathetic flare (e.g., Biesecker & Thompson 2000), activates distant filaments (e.g., Dodson 1949), or causes the oscillation of a remote filament, as observed in He I 10830 Å (Gilbert et al. 2008), as well as in the EUV band with a transverse mode (Hershaw et al. 2011; Gosain & Foullon 2012). On the other hand, MHD oscillations in different modes are also observed during the flaring process, e.g., the global sausage mode (Nakariakov et al. 2003), the kink mode in a magnetically linked large loop (Foullon et al. 2005), quasi-periodic pulsations (QPP; Nakariakov et al. 2005), or a fast-mode shock (Huang & Lin 2006; Asai et al. 2008). Among them, QPP is suggested as observational evidence of the magnetic reconnection process (Tan et al. 2007) and also appears in stellar flares with similar manifestations (e.g., Mathioudakis et al. 2003). The close correlation of the coronal waves to flares/CMEs, indicate that, in addition to being the product of a nearby eruption, such a fast propagating disturbance could also be the trigger of a remote eruption, e.g., exciting the sympathetic solar activity.

Excitation of different activities by the MHD wave is often investigated via numerical experiments. Zaitsev & Stepanov (1982) suggested that the flaring QPP can be modulated based on sausage oscillations. In the work of Asai et al. (2001), QPP is invoked by the fast wave periodically modulating the distance between the slow shocks at the magnetic reconnection site. A current-carrying active region (AR) was suggested to be destabilized by the impact of a coronal wave (e.g., Ofman & Thompson 2002). McLaughlin & Hood (2005) noticed that the electric current density can greatly increase in the vicinity of a null point as triggered by the interaction of an aperiodic fast magnetosonic pulse with neutral points. A 2D simulation was performed by Nakariakov et al. (2006) to further find that fast MHD oscillations can periodically trigger magnetic reconnection by modulating the periodic current in the null point region, and produce QPP when it transports in loops nearby. Based on the catastrophe model, Xie et al. (2019) demonstrated that different disturbances like a fast-mode shock can be produced by solar eruptions and would be manifested as distinct EUV waves. EUV waves are mostly understood physically as fast-mode large-amplitude waves or shocks that are initially driven by the lateral impulsive expansion of a CME (e.g., Pomomel et al. 2008; Veronig et al. 2008, 2018; Patsourakos et al. 2010; Downs et al. 2012; Long et al. 2017). One topic yet to be understood is the probable contribution of coronal waves in triggering sympathetic solar activity. According to the three-dimensional MHD model, several magnetic flux ropes (MFRs) were simulated to sympathetically erupt in a multipolar configuration by Török et al. (2011), in which the main interacting mechanisms were attributed to magnetic reconnection and MHD instability. We explore in detail all the possible causes of magnetic reconnections taking place one after another. Fast coronal waves are frequently produced during solar eruptions, which may be probable candidates leading to sympathetic activity; thus, they require attention, especially from observations. Previously, Zhou et al. (2019) studied a set of successive eruptive events on 2012 March 7. They emphasized the identification of a large-scale MFR connecting ARs 11429 to 11430, and a proceeding external magnetic reconnection (EMR) leading to the eruption of the MFR. In the present work, the same set of eruptions is revisited to explore how the key EMR is triggered and what the causal physics between the first and second sympathetic eruptions is. A fast coronal wave invoked by the first eruption is found as a new candidate to trigger the EMR and the later flare/CME. In Section 2, we briefly introduce observations and present the results deduced from the observations, followed by a discussion and our conclusions in Section 3.

2. Observations and Results

The analysis is based on observations from SDO, STEREO, and SOHO as well as the radio data from the Hiraiso Radio Spectrograph (HIRAS; Kondo et al. 1995) and Wind/WAVES (Bougeret et al. 1995). EUV data from SDO/AIA provide detailed information on six wavebands with a typical cadence of 12 s and a pixel size of 0.6. The Helioseismic and Magnetic Imager (Hoeksema et al. 2014) aboard SOHO gives the strength of the photospheric magnetic field with a time cadence of 45 s and a pixel size of 0.75. The solar rotation effect on all SDO data is removed by registering to 00:00 UT on 2012 March 7. STEREO-A (STA) and STEREO-B (STB) record the propagating coronal wave ahead of the related CMEs from the side with trivial projection effects. In addition, coronal field strength is estimated based on the 3D coronal magnetic field model constructed by the flux rope insertion method (van Ballegooijen 2004; Su et al. 2009, 2011).

2.1. A Summarization of EMR and Three MFRs Identified during the Eruptions on 2012 March 7

The time sequence of eruptions on 2012 March 7 is summarized in Table 1. Figure 1 shows the identifications of three MFRs and the EMR as discussed in Zhou et al. (2019). Here EMR describes the magnetic reconnection process that takes place high between a magnetic arcade and the magnetic fields outside this arcade (e.g., Chen et al. 2016; Zhou et al. 2017, 2019; Hou et al. 2020). The panels of Figure 1 are mainly extracted from Figures 1 and 2 of Zhou et al. (2019). In the EUV image in 171 Å of Figure 1(a), three MFRs, namely MFRs 1 to 3 are marked by three black curves, and the coronal loops C1 to C5 are highlighted by the white curves to constitute a null point region. Figures 1(b)–(c) are composites of running-difference images in three wavelengths of 131 Å, 171 Å, and 211 Å to display the EUV waves W1 and W2 manifested as red propagating fronts. The EMR is displayed in Figures 1(d)–(h) (see also Figure 2 of Zhou et al. 2019). Figure 1(e) shows the time-sequence of the brightness distribution in EUV
171 Å along the slice AB in Figure 1(d). W1 made C1 oscillate about 40 minutes before four EMRs (E1–E4). E1 to E3 produced obvious bidirectional flows with linearly fitting speeds $\geq 200$ km s$^{-1}$. Figure 1(f) presents the time profiles of GOES X-ray flux in 1–8 Å (red) and radio flux (black) to show EMRs occurring before the X1.3 flare. According to the radio spectrum (Figures 1(g)–(h)), E1 is also detected with the manifestation of QPP property in radio observation. The current work emphasizes identification of the causal physics of EMR, and the new role of the fast-mode shock in triggering the sympathetic eruption. The corresponding analysis will be presented in the following sections.

2.2. Fast EUV Waves Related to Successive Eruptions

Three MFRs successively erupted on 2012 March 7 associated with three fast coronal waves and flares/CMEs. As identified by Zhou et al. (2019), the second MFR is a large-scale structure connecting ARs 11429 to 11430. It became unstable and erupted after the occurrence of an EMR at the top. Observations show that this EMR region is disturbed by a fast coronal wave produced by the eruption of the first X5.4 flare-associated MFR in AR 11429. It is believed that such a fast coronal wave could be a candidate driver of the key EMR.

Three successive fast coronal waves were well observed in EUV passbands, especially in 211 Å as illustrated in Figure 2. The original EUV images of Figures 2(a)–(f) show coronal structures modified by eruptions. Three EUV waves are clearly seen as an enhanced EUV density region with sharp fronts in the running-difference images of Figures 2(g)–(i) (see the yellow arches labeled by W1, W2, and W3) with difference time of 2 minutes. When the X5.4 class flare peaked at 00:20 UT, W1 was seen to sweep upward over the coronal loops connecting ARs 11429 to 11430 (see the white solid arrows and the label of C1), and raised C1 to a new height at the end of the X5.4 flare at 00:40 UT. At about 00:52 UT, the EMR (pink arrows in Figure 2(d)) intermittently started with the manifestations of small-scale EUV eruptions (see also Zhou et al. 2019).

In a short time, the second large-scale MFR erupted at about 01:00 UT to produce W2 as shown in Figure 2(d). Immediately, the third MFR in the AR 11429 erupted leading to W3 with a clear appearance at about 01:11 UT (see the yellow curve in Figure 2(e)). Eventually, a trans-equatorial coronal dimming was created (see the dashed arrow in Figures 2(a)–(f)). This suggests that the three successive eruptions are related to one another, and the fast wave caused by the prior eruption plays an essential role in triggering the eruption afterwards.

Physical properties of coronal waves, e.g., the speeds projected on the sky plane, and the temperature and density of local corona, can be learned from the spacetime map (right panels) over a narrow region AB (left panels) during the propagation of the wave noses as shown in Figure 3. What these panels display are, from the top to the bottom, the filtergrams in the base-difference data of 211 and 171 Å by subtracting the one at 00:00 UT, distributions of the temperature and the density deduced via differential emission measure (DEM) approach as discussed in Cheng et al. (2012). The DEM code “xrt_dem_iterative2.pro” in the SSW package was originally designed for the Hinode X-ray Telescope data (Golub et al. 2004; Weber et al. 2004). It was then modified to compute the DEM based on the AIA data (see also Schmelz et al. 2010; Winebarger et al. 2011; Cheng et al. 2012). The DN counts in each of the six EUV wavelengths are divided by the exposure time and spatially averaged over all pixels in the area (see Cheng et al. 2012). The averaged count rates were used as the input of the “xrt_dem_iterative2.pro” routine to calculate the DEM. The region DEM shows a broad temperature distribution from about 1.7 to 11 MK (log T = 6.2–7.0). The total emission measure (EM) is calculated according to $EM = \int DEM(T) dT$ and is located in the range of $[3.3 \times 10^{26}, 7.9 \times 10^{29}]$ cm$^{-5}$. Since the filling factor of the plasma is unknown, it is assumed to be 1 in the density calculation. An uncertainty of 20% is considered as a lower limit for estimating T and EM. The right panels display the

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Table 1

| Time     | Observations                                                                 | Explanation                                                                 |
|----------|------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| 00:02–00:40 UT | An X5.4 flare occurred in AR 11429 with a peak at 00:24 UT                  | The X5.4 flare/CME is associated with the eruption of the first MFR located in the north PIL of AR 11429. |
| 00:15 UT  | The first CME related to the X5.4 flare first appeared in the field of view of STB cor1 | W1 was produced by the X5.4 flare/CME. C1 was disturbed by the W1 to rise up. |
| 00:10–00:35 UT | W1 oscillated coronal loops C1 connecting ARs 11429 and 11430, and lifted it up ≥25 Mm | It is identified as EMR process that occurred in the null region near the top of C1, which is indicated by the converging interface of C1–C4 and extrapolations. |
| 00:52–01:06 UT | Small-scale eruptions occurred at the top of C1 and manifested by bidirectional EUV outflow and the character of radio spectrum QPP | This CME is related to the eruption of a large-scale MFR connecting ARs 11429 and 11430, namely MFR3. MFR 3 is well identified to have a temperature ≥10 MK. Its two footpoints are located in the negative and positive polarities from ARs 11429 and 11430, respectively, and have the same negative helicity but opposite current. |
| 00:55 UT  | The second CME appeared in the field of view of STB cor1. It originated near the top of C1 with two flare ribbons between ARs 11429 and 11430, and propagated toward the Earth. | This CME is related to the eruption of the MFR 2, which is located in the south PIL of AR 11429. |
| 01:05–01:23 UT | An X1.3 flare occurred in AR 11429 with a peak at 01:14 UT                  |                                                                           |
| 01:25 UT  | The third fast CME related to the X1.3 flare first appeared in the field of view of STB cor1 |                                                                           |

Note. EMR—external magnetic reconnection; C1—coronal loops connecting ARs 11429 and 11430; QPP—quasi-period pulsation; PIL—polarity inversion line.
resultant spacetime maps of the corresponding parameters during 00:00–01:40 UT. The right four rows of images are displayed in the range of \([-20, 20]\) DN s\(^{-1}\), \([-90, 90]\) DN s\(^{-1}\), \([4.4 \times 10^5, 8.9 \times 10^6]\) K, and \([1.1 \times 10^{26}, 2.3 \times 10^{27}]\) cm\(^{-5}\), respectively. The maximum temperature and EM for W1 are \(5.6 \times 10^6\) K and \(1.2 \times 10^{27}\) cm\(^{-5}\). The coronal waves appear as a bright moving feature in 211 Å of Figure 3(b), but as dark ones in 171 Å (Figure 3(d)). This can be interpreted as emission decrease in the 171 Å channel due to heating to higher temperatures as discussed in Vanninathan et al. (2015). By linearly fitting (see the dashed oblique lines), W1 and W2 are estimated to have speeds of 550 and 500 km s\(^{-1}\) projected in the sky plane observed by SDO/AIA, respectively. The W1-related CME1 structure can also be seen as a propagating brightening structure in Figure 3(b), and has a slower velocity of about 180 km s\(^{-1}\) than that of the fast W1 ahead. These speeds give lower estimates, since we only observe the projected kinematics: EUV waves are propagating at a certain height above the curved solar surface (Kienreich et al. 2009; Podladchikova et al. 2019), and the measured CME kinematics is projected against the plane-of-the-sky.

In order to determine the mode of the coronal waves, it is necessary to estimate the local Alfvén speeds \(V_A\) around C1 that were disturbed by the eruption. According to \(V_A = B/\sqrt{\mu_0 \cdot \rho} \approx 2.18 \times 10^7 B/\sqrt{n_e}\), with \(B\) being the magnetic field strength on C1 at the height of 0.7 \(R_s\) as detected by STEREO, which is about 3 G based on the magnetic field model constructed using the flux rope-inserting method (Su et al. 2019).
2009, 2011), and $T$ and $n_i$ being the associated average temperature and density of the local corona. According to Aschwanden et al. (1999), $n_i = EM/w$, with EM being the EM and $w$ being the width of C1 under the assumption of a circular cross-section (see also Zhou et al. 2016). We select the regions right ahead of wave fronts (see white solid bars) in the spacetime maps in Figures 3(f) and (h), and get $T$ of 5.3 MK and 4.8 MK, EM of $8.4 \times 10^{26} \text{cm}^{-5}$ and $8.3 \times 10^{26} \text{cm}^{-5}$, respectively. Their mean density $n_i$ corresponds to $6.2 \times 10^8 \text{cm}^{-3}$ and $6.1 \times 10^8 \text{cm}^{-3}$ with the loop width $w$ measured as about 22 Mm. Therefore, W1 and W2 propagated in the corona with Alfvén speeds $V_A$ of about 260 km s$^{-1}$. Considering a possible uncertainty of about 10%–20% in calculating the temperature, density, and width of the coronal loops, the local Alfvén speeds corresponding to W1 and W2 should not exceed 330 km s$^{-1}$. Consequently, as their speeds are faster than the local Alfvén speed, we identify W1 and W2 as fast-mode shocks propagating through the corona.

2.3. Fast-mode Shocks Exist ahead of CME1 and CME2

Figure 4 shows the first CME (CME1 hereafter) associated with W1 during 00:15–01:24 UT, and the second CME (CME2 hereafter) related to W2 during 00:55–02:24 UT observed by the COR1 and COR2 coronagraph on board STA (left panel) and STB (right panel) in the top two rows. In order to show the whole propagating process clearly, the composites of images obtained by STA and STB in which the CME front can be recognized at different moments are displayed in Figures 4(a) through (d). Connecting every adjacent two forefronts as denoted by small circles via a dashed line indicates the straightforward propagation of CME1 and the apparent

![Figure 2. W1–W3 related three fast successive coronal waves shown in the original ones (a)–(f) and the running-difference images (g)–(i) in 211 Å. Yellow curves highlight the fronts of W1–W3. Arrows of solid white, dotted white, and solid pink denote the coronal loops connecting ARs 11429 and 11430, and the trans-equatorial coronal dimming, as well as the EMR, respectively. An animation of the original and running-difference images at 211 Å is available in the online Journal. The animated images, which have the same annotations as the static figure, run from 00:02 to 01:30 UT. (An animation of this figure is available.)](image-url)
deflection of CME2 in the direction leaving the Sun. Figure 4(e) illustrates height–time variations of the two CME fronts. Here the height is measured from the solar center. Blue and red colors denote observations from STA and STB, respectively. The spatial locations of STA/STB, the Earth/SDO, and the Sun are shown in the bottom right corner of Figure 4(e).

Combining observations from STA with those from STB, we could deduce reasonable values for velocities of CME1 and CME2. The height–time distributions of CMEs in Figure 4(e) observed by STA (red) and STB (blue) clearly show two phases of a CME, i.e., the initial phase followed by the impulsive one, which are linearly fitted with solid lines, respectively. In order to estimate uncertainties of CME heights, we repeatedly trace CME fronts in the sky plane at each moment 10 times to get 3σ of the measured distances as the error bars. The errors of velocities are obtained from the Monte-Carlo simulations with the uncertainties of CME front situations. We use the maximum velocity uncertainty in different stages of a CME as the corresponding error bars. As a result, CME1 has an initial speed of 2060 ± 270 km s⁻¹ from 00:15 to 00:25 UT, and a later impulsive speed of 3290 ± 530 km s⁻¹ observed by STB, corresponding to 2240 ± 270 km s⁻¹ and 2580 ± 530 km s⁻¹ in the field of view of STA. With a similar fitting method, CME2 has an initial speed of 730 ± 270 km s⁻¹ from 00:53 to 01:15 UT and an impulsive speed of 1690 ± 530 km s⁻¹ from STA, which are 930 ± 270 km s⁻¹ and 2440 ± 530 km s⁻¹ from STB. Comparing with the local Alfvén speed of a few 10² km s⁻¹, we believe that the occurrence of the fast-mode shocks in front of both CMEs are inevitable.

Type-II radio bursts are usually considered to be good manifestations to identify a coronal shock (e.g., Uchida 1960). Figure 5 shows the radio dynamic spectrum in the frequency range from 20 kHz to 500 MHz obtained from Wind/Waves and HiRAS during 00:25–03:00 UT covering two times of eruptions. Two sets of type-II radio burst signals covering time intervals of 00:25–03:00 UT and 01:10–01:25 UT can be recognized (see white and black dashed curves). The initial frequencies of the fundamental components are located at 55 and 75 MHz for the type-II radio bursts driven by the shocks associated with two eruptions, respectively.
empirical model about the coronal density distribution of Sittler & Guhathakurta (1999), the density at the coronal base is considered to be $10^{10}$ cm$^{-3}$. The initial heights of the two shocks were deduced at about $0.9 R_e$ and $0.8 R_e$, respectively, which is consistent with the observations from STA/STB. Since the noses of W1 and W2 propagated in the direction along the slice AB (see the left panels of Figure 3), type-II radio bursts are suggested to relate to the eruptions in this direction. Feng et al. (2020) recently constructed the three-dimensional configurations of the wave W1 surfaces using three techniques. They suggested a similar result that the same W1 nose increased from the speeds 600 to 800 km s$^{-1}$ across the solar disk with the manifestation of EUV disturbances to a much higher speed up to 3800 km s$^{-1}$ in the extended corona.

We discussed that W1 and W2 in EUV observations from SDO may be the footprints in the lower corona of the corresponding shocks driven by CME1 and CME2, which are the enhanced EUV emission at the wave front caused by the downward push and compression of the plasma at the base due to the coronal shock or large-amplitude wave (e.g., Warmuth et al. 2005; Harra et al. 2011; Veronig et al. 2011). In any case, the current work shows that shock waves were produced during the successive eruptions on 2012 March 7 whether in the lower corona or in the higher one. Combining the analysis of observations, a reasonable physical mechanism about the shock wave is deducted to trigger the key EMR causing a sympathetic eruption.

3. Discussions and Conclusion

In order to understand how the X5.4 flare-related shock wave triggers magnetic reconnection, we need to check the 3D
magnetic topology of the erupting structures at 00:00 UT. The 3D magnetic topology covering a trans-equatorial region was reproduced according to magnetic field modeling using the flux rope insertion method (van Ballegooijen 2004; Su et al. 2009, 2011). A flux bundle is inserted with an initial axial flux of $4 \times 10^{20}$ Mx and a poloidal flux of 0 Mx cm$^{-1}$ in the best-fit model. It then gradually evolved into a flux rope with increasing poloidal flux due to magnetic reconnections with the surrounding fields during the magneto-frictional relaxation process as discussed in Su et al. (2011). After 30,000-iteration relaxations, the initial inserted flux bundle was turned into a flux rope as shown in Figure 6. The size of the modeled high-resolution magnetic field region is about 59° in longitude and 80° in latitude on the solar disk up to a height of 1.25 $R_\odot$ above the solar surface, and the spatial resolution in the low corona is 0.002 $R_\odot$. Figure 6 shows the 3D constructed configuration seen from the top (left) and from the side (right), which manifest topological features similar to those observed in EUV by SDO/AIA. Red lines are for the large-scale MFR3 connecting ARs 11429 to 11430, above which four sets of
field lines (“C1–C4”); indicated in yellow and green colors) consist of two X-type configurations constituting the null point region.

The modeled 3D coronal magnetic configurations displayed in Figure 6 show how the shock triggers the EMR. Driven by CME 1, the fast-mode shock associated with W1 (see also Figures 2(g), 3(a), and (b)) globally propagated with a strong front toward the loop top of C1 and making it disturb between ARs 11429 and 11430 for about 40 minutes since 00:15 UT. At about 00:52 UT, EMR occurred in the null point region around C1, manifested by small-scale EUV eruptions in FOV of SDO/AIA (see also Figures 1(d), (e), 2(d), and 2(e)), and the typical QPP features (see Figures 1(f) through (h)) revealed by radio observations (see Tan 2008; Zhou et al. 2019). With the occurrence of the intermittent EMR, the force that results in the overlying magnetic field and keeps the configuration in the equilibrium is weakened, leading to the eruption of the large-scale MFR3 (see also Figure 1(a)) at about 01:03 UT. Our observations here show that the W1-related fast shock was followed by the EMR and the large MFR3 erupting as a fast halo CME. The physical process behind this scenario could be the accumulation of the electric current in the region near the null point, which is triggered periodically by the fast magnetoo-oscillation as W1 passed through the null point region. This is consistent with the simulation results of McLaughlin & Hood (2005) and Nakariakov et al. (2006). In addition, we also suggest that W1 might greatly increase the local turbulence in the null point region, giving rise to a large anomalous resistivity that eventually invoked EMR.

In spirit of the works of McLaughlin & Hood (2005) and Nakariakov et al. (2006), we revisit the three successive eruptions taking place on 2012 March 7. Propagating characteristics of the CMEs in two eruptions indicate the occurrence of the fast-mode shock, which are confirmed by the type-II radio burst observed in the same time intervals when they were observed. By analyzing the initial altitudes of the two shocks, and looking into the magnetic configurations associated, a null point region was recognized, and the fast-mode shock driven the first CME passing through the region around the null point. According to McLaughlin & Hood (2005) and Nakariakov et al. (2006), what we observed in the present event might result from the electric current intensity exceeding the threshold value, which leads to a spontaneous magnetic reconnection taking place in the null point region, and alternates the topological structure of the related magnetic configuration, eventually yielding the consequent eruption. This scenario seems to suggest that the fast-mode shock invokes an oscillation in the nearby magnetic structure including a null point, triggering the magnetic reconnection process at the null point region, and further the sympathetic eruption in the related magnetic configuration. More observations in the future to verify this scenario are surely needed.

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