A Confined Two-peaked Solar Flare Observed by EAST and SDO (Postprint)

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Abstract

The solar flare is one of the most violent explosions, and can disturb the near-Earth space weather. Except for commonly single-peaked solar flares in soft X-ray, some special flares show intriguing a two-peak feature that is deserved much more attentions. Here, we reported a confined two-peaked solar flare and analyzed the associated eruptions using high-quality observations from Educational Adaptive-optics Solar Telescope and Solar Dynamics Observatory. Before the flare, a magnetic flux rope (MFR) formed through partially tether-cutting reconnection between two sheared arches. The flare occurred after the MFR eruption that was confined by the overlying strong field. Interestingly, a small underlying filament immediately erupted, which was possibly destabilized by the flare ribbon. The successive eruptions were confirmed by the analysis of the emission measure and the reconnection fluxes. Therefore, we suggest that the two peaks of the confined solar flare are corresponding to two episodes of magnetic reconnection during the successive eruptions of the MFR and the underlying filament.

Full Text

Preamble

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A Confined Two-peaked Solar Flare Observed by EAST and SDO

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Abstract

Solar flares are among the most violent explosions on the Sun and can significantly disturb near-Earth space weather. While most flares exhibit a single peak in soft X-ray emission, some special events display an intriguing two-peak feature that deserves greater attention. Here we report a confined two-peaked solar flare and analyze its associated eruptions using high-quality observations from the Educational Adaptive-optics Solar Telescope (EAST) and the Solar Dynamics Observatory (SDO). Prior to the flare, a magnetic flux rope (MFR) formed through partial tether-cutting reconnection between two sheared arches. The flare occurred following the eruption of this MFR, which was confined by overlying strong magnetic fields. Interestingly, a smaller underlying filament immediately erupted afterward, possibly destabilized by the flare ribbons. The successive eruptions were confirmed through analysis of emission measure and reconnection fluxes. We therefore suggest that the two peaks of this confined solar flare correspond to two distinct episodes of magnetic reconnection during the successive eruptions of the MFR and the underlying filament.

Key words: Sun: activity -Sun: corona -Sun: flares -Sun: magnetic fields -Sun: filaments -prominences

Online material: animations

1. Introduction

Solar eruptions, including solar flares and coronal mass ejections (CMEs), are violent explosions that release high-energy ions and large amounts of magnetized plasma into interplanetary space, significantly influencing space weather. These eruptions are generally believed to involve fundamental structures such as magnetic flux ropes (MFRs) and filaments (Liu 2020; Patsourakos et al. 2020). MFRs are groups of coherently twisted magnetic field lines wrapped around a central axis, while filaments are cold, dense plasma suspended in the hot corona (Martin 1998; Mackay et al. 2010). Both are twisted/sheared magnetic structures filled with magnetic energy (Forbes 2000; Low 2001). During an eruption, this magnetic energy is converted into heat, bulk kinetic energy, and fast particle energy. However, the trigger mechanisms and subsequent evolution of solar eruptions remain incompletely understood.

Over the past decades, many physical models have been proposed to interpret the trigger mechanisms of solar eruptions. These models fall mainly into two categories: magnetic reconnection models, such as the tether-cutting model (Moore et al. 2001), flux-cancellation model (van Ballegooijen & Martens 1989), and breakout model (Antiochos et al. 1999); and ideal magnetohydrodynamics (MHD) models, such as the kink instability model (Török et al. 2004; Fan 2005) and torus instability model (Kliem & Török 2006). Following initiation, solar flares are intimately related to CMEs, though not every flare is accompanied by a CME. Based on this criterion, solar flares are divided into two categories: eruptive flares and confined flares. Confined flares are often accompanied by failed or confined eruptions of filaments or MFRs. In these failed/confined eruptions, the filament/MFR first experiences rapid acceleration, then quickly decelerates for various reasons, eventually stopping at a certain height or falling back to the Sun without producing a CME (Ji et al. 2003; Yang et al. 2019).

Among the numerous solar flares observed, most show a single peak in GOES X-ray profiles during their impulsive phase. However, some unique flares exhibit a two-peaked feature during the impulsive phase that warrants attention, though such observations remain rare. Ning et al. (2018) analyzed a confined M2-class flare with a clear two-peak structure observed in hard X-rays, revealing two distinct steps of loop-loop interaction induced by the two-peaked flare. They further showed that the first step of energy release was mainly for nonthermal particle acceleration, while the second step was primarily for plasma heating, through analysis of data from RHESSI and NoRH. Zheng et al. (2023) reported another case with a two-peak feature in soft X-ray profiles and their derivatives, suggesting that this feature was caused by the eruption and deformation of an MFR. Therefore, two-peaked flares often contain more physical information and correspond to more complex evolutionary processes. Studying such events can help us better understand the evolution of solar eruptions.

Additionally, some observations have reported that solar eruptions can be triggered by moving magnetic features (MMFs) (Sterling et al. 2010; Paraschiv et al. 2020; Joshi et al. 2022). MMFs are persistent activities around sunspots (Harvey & Harvey 1973). A sunspot is typically surrounded, at least partially, by a zone of relatively stationary magnetic field known as the sunspot' s "moat." MMFs appear as small magnetic features that move away from the sunspot toward the boundary of the moat region, usually with higher velocities than the average moat flow. MMFs can be classified into two groups based on whether their emerged polarities are coupled, and further divided into three types. Type I MMFs are small magnetic bipoles, while Type II and Type III MMFs are unipolar features with the same or opposite polarity as the parent sunspot, respectively. After emergence, MMFs can continuously converge toward and cancel with polarity inversion lines (PILs), thereby triggering solar eruptions in a manner similar to the flux-cancellation model (van Ballegooijen & Martens 1989).

In this article, we report a two-peaked confined flare associated with MMFs. This two-peaked flare was induced by successive eruptions of an MFR and a filament, with neither eruption producing a CME.

2. Observations and Data Analysis

The confined two-peaked flare occurred in NOAA active region (AR) 13076 on 2022 August 12, associated with successive eruptions of an MFR and a filament. We primarily used data from the Solar Dynamics Observatory (SDO) (Pesnell et al. 2012) and the Educational Adaptive-optics Solar Telescope (EAST) (Rao et al. 2022). The formation and eruption of the MFR were recorded by the Atmospheric Imaging Assembly (AIA) (Lemen et al. 2012) onboard SDO. The AIA images have a pixel size of 0.6 and a cadence of 12 s. The filament eruption was captured by high-resolution observations from EAST and the CHASE/Hα Imaging Spectrograph (HIS) (Li et al. 2022). EAST was built at the Shanghai Astronomy Museum with pixel resolutions of 0.12 for Hα and TiO. CHASE/HIS provides Hα images with a pixel spatial resolution of 0.52 . The MMFs and magnetic field evolution in the source region were examined using the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) onboard SDO, with a cadence of 45 s and pixel scale of 0.6 .

Additionally, coronal magnetic field lines in AR 13076 were extrapolated using the Potential Field Source Surface (PFSS; Schrijver & De Rosa 2003) package in SolarSoftWare. The flare' s emission properties were investigated using the differential emission measure (DEM) method. The DEM analysis employed the xrt_{{{dem}}_{{iterative2}}}.pro routine in the SolarSoftWare package (Cheng et al. 2012; Song et al. 2014), obtaining EM maps at different temperature ranges from a set of AIA images in six channels (94, 131, 171, 193, 211, and 335 Å).

To reconstruct the three-dimensional magnetic configuration above the source region, the nonlinear force-free field (NLFFF) method was employed based on photospheric vector magnetic fields observed by SDO/HMI. The HMI vector magnetograms were first processed to remove the 180° ambiguity of the transverse components and then corrected for projection effects to create suitable boundary conditions for force-free modeling. The calculations were performed within a box of 161 × 121 × 121 uniformly distributed grid points with $\Delta x = \Delta y = \Delta z = 2$ (Guo et al. 2017). Furthermore, the twist number Tw of the extrapolated 3D magnetic fields was calculated using the method developed by Liu et al. (2016).

3. Results

The overview of AR 13076 and the source region is shown in Figure 1 [Figure 1: see original paper]. AR 13076 consisted mainly of a positive sunspot (P1) surrounded by nearly stationary negative polarities (panel (b)). These formed a diffused moat region around P1. According to AIA 171 Å and the PFSS model, AR 13076 was filled with clusters of magnetic loops and closed magnetic field lines (panel (c)). The source region was located in the southwest part of AR 13076 (cyan box in panel (b)). It involved the main sunspot (P1), the trailing positive polarity (P2), and the surrounding negative polarities (N2-N3).

In addition, an L-shaped filament existed in the source region. The profile of this filament, superimposed on HMI magnetogram maps, was rooted in P1 and N1, with its middle part passing through P2 and N2-N3.

Before the flare, an MFR formed through tether-cutting reconnection between two sheared arches (L1 and L2). The overview of these two sheared arches is presented in the first row of Figure 2 [Figure 2: see original paper]. L1 and L2 were located on the northern and southern sides of the source region, respectively, sheared past each other. The selected profiles of L1 and L2 were superposed on HMI magnetogram maps. L1 was rooted in P1 and N2-N3, while L2 was rooted in P2 and N1. Furthermore, the magnetic field evolution at two adjacent ends of L1 and L2 (P2 and N2-N3) is shown in the second and third rows. Initially, P2 and N2-N3 were separate around 11:59:52 UT on 2022 August 11 (panel (d)), after which P2 and N2 converged toward each other. They made contact around 20:20:37 UT on 2022 August 11 (panel (e)). Subsequently, N2 also moved toward P2 (panels (e)-(f)). To analyze the convergence motion of P2 and N2-N3, a horizontal slice was employed extending from the eastern side of P2 and passing through P2 and N2-N3 (the yellow line). The time-distance plot is shown in panel (g). P2, N2, and N3 converged with speeds of 0.71 km s^{-1}, 0.45 km s^{-1}, and 1.01 km s^{-1}, respectively. Simultaneously, P2 canceled with N2-N3. Panels (e) and (f) show that P2 evolved from a compact shape to a striped shape, while N2-N3 shrank. Note that the southern part of P2 at 06:30:37 UT on 2022 August 12 was considered, as the northern part likely originated from other magnetic flux associated with the sunspot. The magnetic flux for P2 and N2-N3 was measured (green box in panel (d)). After 19:00 UT on 2022 August 11, both positive and negative flux experienced a remarkable decrease. The positive flux decreased by 3.3×10^{20} Mx and the negative flux decreased by 1.7×10^{20} Mx. Therefore, the adjacent ends of L1 and L2 experienced magnetic convergence and cancellation in the photosphere.

Accompanying this magnetic convergence and cancellation, the MFR formed through tether-cutting reconnection, with the formation process presented in Figure 3 [Figure 3: see original paper]. In three examples, brightenings first appeared along L1 (green arrows), after which a flux rope formed (red arrows) connecting the northern end of L1 and the western end of L2. The first example (blue arrow) was particularly notable, as a jet occurred simultaneously with the brightenings. The jet ejected from the southern end of L1 toward the eastern end of L2, tracing a small C-shaped loop. This small C-shaped loop was likely a product of the tether-cutting reconnection. The brightenings, together with the jet and the formed MFR, along with the magnetic convergence and cancellation at the adjacent ends of L1 and L2, are consistent with the physical picture of tether-cutting reconnection. Therefore, the MFR was likely formed by tether-cutting reconnection.

Furthermore, the formation of the MFR was verified using the NLFFF method at 00:00:00 UT and 04:00:00 UT on 2022 August 12 (Figure 4 [Figure 4: see original paper]). The extrapolated magnetic field lines (pink) at 00:00 UT were rooted in P1 and N1, with the middle part passing through P2 and N2-N3, consistent with the magnetic configuration of the formed MFR (panel (a)). The average twist number (Tw) for the region of southern footpoints of the extrapolated magnetic field lines (pink) in the photosphere was then calculated (white dashed box). The values were T at 00:00 UT and T at 04:00 UT. The increase in Tw over time was consistent with the formation process of an MFR. In addition, the twist number exceeded one turn at 04:00 UT, indicating that it had become an MFR before eruption.

The magnetic field was then re-examined and enlarged to focus on the source region. In the source region, continuous MMFs were present. The MMFs and their cancellation with the source region' s PIL are shown in Figure 5 [Figure 5: see original paper]. In two examples (first and second rows), the MMFs are Type I MMFs that emerged as positive-negative couples (blue arrows). Since the sunspot had positive polarity, the emerging negative part of the MMFs was more obvious. The magnetic flux around the boundary of the sunspot (red box) was measured, focusing mainly on the negative flux. It can be seen that the negative flux increased from nearly zero, while the positive flux also showed an overall increasing trend (panel (g)). Therefore, it is confirmed that the MMFs emerged from the sunspot. After emergence, the MMFs moved toward the boundary of the moat region and naturally converged to the source region' s PIL. During this movement, the MMFs canceled with both the polarities of the PIL (green arrows in the first example) and the footpoint of the MFR (cyan arrows in the second example). Note that the magnetic flux cancellation caused by MMFs was continuous, as they continuously emerged from the sunspot (see associated animation). Furthermore, the magnetic flux for the field of view of Figure 5 was measured and presented in panel (h). It shows that the positive magnetic flux experienced an abrupt decrease at the onset of the eruption (black vertical line). The negative flux showed bumps, indicating magnetic flux emergence and cancellation.

The formed MFR was likely destabilized by magnetic flux cancellation intimately associated with the MMFs and began to erupt at around 04:53 UT (Figure 6 [Figure 6: see original paper]). Two bright flare ribbons (white arrows) and post-flare loops (yellow arrow in panel (e)) first appeared in the source region at the onset of the MFR eruption. The flare ribbons shared a nearly perpendicular configuration. The post-flare loops were weak and faded quickly. At this time, the erupted MFR was weak but became obvious at high altitude around 04:57 UT (red arrows in panels (e) and (f)). During this phase, the erupted MFR rose slightly and stopped at a height (see associated animation). The eruption of the MFR was confined and eventually faded away.

The eruption of the MFR likely influenced the underlying filament, which erupted soon after the northern ribbons appeared beneath it (blue arrows in panel (a) of Figure 6 [Figure 6: see original paper]). The filament showed an overall western eruption and was accompanied by untwisting motion (purple arrows in the first column of Figure 7 [Figure 7: see original paper] and associated animation). The ribbons transformed to locations around the two ends of the filament (white arrows in the second column). Clearly, the erupted filament was confined by its overlying magnetic loops (L1; orange arrows). Hence, the filament eruption was also confined.

The EM maps clearly reveal the two eruptions at three different temperature ranges: 0.3-1.0 MK (low), 1.0-10 MK (middle), and 10.0-25.0 MK (high) (Figure 8 [Figure 8: see original paper]). In the first eruption, the flare ribbons were evident at all three temperature ranges (white arrows in the first column), the post-flare loops were visible at the middle temperature range (yellow arrow), and the erupted MFR mainly appeared at the high temperature range (red arrows). In the second eruption, the erupted filament material was unambiguous at the low temperature range (purple arrows in the second column). It can be seen that the erupted filament was confined by overlying loops that appeared at the middle temperature range (orange arrow). In addition, emission at the two ends of the filament was strong (white arrow in panel (b)), consistent with the location of the ribbons during the filament eruption.

The successive eruptions of the MFR and the filament were captured by the GOES satellite (Figure 9 [Figure 9: see original paper]). The SXR flux and its derivative profile clearly revealed two distinct peaks. The first peak occurred at 04:58 UT while the second peak occurred at 05:10 UT. This is consistent with the two-peak feature in intensity flux for the source region in AIA 1600, 304, and 131 Å. In addition, the contours of flare ribbons were superposed on magnetogram maps. As described in Zhu et al. (2018) and Kazachenko et al. (2017), the reconnected flux can be roughly estimated as the magnetic flux swept by flare ribbons at a given time. Both the reconnection flux and reconnection rate were calculated and presented in panels (f) and (g). They also showed similar two-peaked features as those in SXR, its derivative, and the intensity profiles for the source region. Hence, it is confirmed that the confined two-peaked flare was induced by the successive eruptions of the MFR and the filament. Both flares lasted for about 6 minutes each, though the first peak in the SXR derivative profile was much stronger than the second peak.

4. Conclusions and Discussion

Combining high-resolution observations from EAST and SDO, we report a confined two-peaked flare induced by successive eruptions of an MFR and a filament. Before the eruptions, continuous MMFs existed in the source region and the MFR formed through tether-cutting reconnection between two sheared arches (L1 and L2). The flare occurred after the MFR eruption, which was confined by overlying strong fields. Interestingly, a small underlying filament immediately erupted, possibly destabilized by the flare ribbons. The successive eruptions were confirmed through analysis of emission measure and reconnection fluxes, consistent with the two-peaked flare recorded in GOES SXR and its derivative profiles.

The MFR was likely formed by tether-cutting reconnection between two sheared arches (L1 and L2). Direct observations of tether-cutting reconnection are rare (Chen et al. 2014, 2018). In this case, L1 and L2 were sheared past each other, providing a favorable configuration for tether-cutting reconnection. The reconnection was likely driven by the converging motion of two adjacent ends of the sheared arches in the photosphere. As products of tether-cutting reconnection, the small C-shaped loop traced by the jet, the flux rope, and the brightenings appeared almost simultaneously. The magnetic cancellation at the adjacent ends in the photosphere was also observed accompanying the tether-cutting reconnection. Based on these observations, we infer that tether-cutting reconnection occurred between the two sheared arches to form the MFR. Additionally, L1 and L2 likely underwent partial tether-cutting reconnection, as the reconnection was relatively weak and L1 still confined the erupted filament after the MFR eruption. This partial tether-cutting reconnection is similar to the case described in Zheng et al. (2019).

The abrupt decrease of positive magnetic flux has an intimate relationship with the eruption onset, likely indicating that the eruption was triggered by magnetic flux cancellation. This cancellation was accompanied by continuous MMFs. As shown in Figure 5 [Figure 5: see original paper], the cancellation site associated with MMFs occurred mainly at the footpoint of the MFR and the source region's PIL. On one hand, magnetic flux emergence or cancellation around the footpoint of an MFR can influence its stability (Chen & Shibata 2000; Lin et al. 2001). On the other hand, cancellation at the PIL can accumulate energy and flux for the overlying MFR (van Ballegooijen & Martens 1989). When the accumulated energy for an outward eruption exceeds the energy of the restraining magnetic field, the MFR becomes unstable (Amari et al. 2010; Chen 2011; Sterling et al. 2011). While we cannot rule out cancellation caused by other magnetic polarities in the source region, we maintain that MMFs played an important role in triggering the eruption, as the continuous MMF flow brought sustained magnetic cancellation at both the PIL and the footpoint of the MFR.

The confined two-peaked flare indicates two episodes of magnetic reconnection during the successive eruptions of the MFR and the underlying filament. The first episode was likely caused by the eruption of the formed MFR. Unlike cases where formed MFRs erupt immediately after formation (Liu et al. 2010; Joshi et al. 2015), the MFR in this event disappeared from AIA 131 and 94 Å channels. It remains unclear whether the formed MFRs truly disappeared or if this was simply due to temperature decreases. A related event showed that a formed MFR could disappear from AIA channels while still existing in the source region, as evidenced by filament formation through coronal condensation (see Figure 3 and associated animation in Li et al. 2021). Moreover, the NLFFF method employed in Figure 4 [Figure 4: see original paper] confirmed that an MFR existed before eruption. The twist number of the MFR exceeded one turn but was still relatively low, which likely kept it stable after formation.

Regarding the second eruption, it was confined like the MFR eruption, though the MFR likely erupted more fully than the filament. The MFR eruption was accompanied by obvious post-flare loops and two bright flare ribbons, while the filament eruption only produced two compact ribbons around its ends. The SXR derivative profile also reveals that the first peak was much stronger than the second, possibly indicating that nonthermal emissions in the MFR eruption were more intense than those in the filament eruption.

Based on these results and discussions, we propose a scenario to interpret the confined two-peaked flare (Figure 10 [Figure 10: see original paper]). In the source region, there existed two sheared arches (L1 and L2; yellow and cyan lines in panel (a)) in the northern and southern sides, respectively. A filament underlay L1 (purple line). Before eruption, L1 and L2 partially participated in tether-cutting reconnection (“X” symbol in panel (a)). As a result, an MFR formed (yellow-cyan line in panel (b)) with lower post-reconnection loops (black dotted lines). The formed MFR was likely destabilized by magnetic flux cancellation intimately associated with continuous MMFs in the source region and rose upward (panel (c)). The rising MFR stretched overlying loops above it, causing anti-parallel magnetic field lines to approach each other (upper orange line), and magnetic reconnection occurred (“X” symbol). As a product of this reconnection, post-flare loops appeared at low altitude (lower orange line) and flare ribbons extended (white patches with red contours). The rising MFR eventually stopped at a height and gradually faded away (yellow-cyan line in panel (d)). The underlying filament was likely destabilized by ribbons produced during the MFR eruption (green asterisk in panel (c)). It erupted soon after the ribbons appeared beneath it. The erupted filament likely stretched the overlying loops (upper black lines) and produced lower post-reconnection loops (lower black dotted lines) through magnetic reconnection. Ribbons transformed to the locations of the filament’ s two ends (white patches with red contours in panel (d)). Eventually, the filament was also confined by overlying loops (L1; yellow lines).

In summary, this article reports a case study of a confined two-peaked flare and analyzes the associated eruptions. We suggest that the confined two-peaked flare was caused by two distinct episodes of magnetic reconnection that took place during the successive eruptions of the MFR and the underlying filament. However, more observations and simulations of two-peaked solar flares are required to improve our understanding of the complex evolution of solar eruptions.

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