Sequential Lid Removal in a Triple-decker Chain of CME-producing Solar Eruptions

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Abstract

We investigate the onsets of three consecutive coronal mass ejection (CME) eruptions in 12 h from a large bipolar active region (AR) observed by the Solar Dynamics Observatory (SDO), the Solar Terrestrial Relations Observatory (STEREO), the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), and the Geostationary Operational Environmental Satellite (GOES). Evidently, the AR initially had a “triple-decker” configuration: three flux ropes in a vertical stack above the polarity inversion line (PIL). Upon being bumped by a confined eruption of the middle flux rope, the top flux rope erupts to make the first CME and its accompanying AR-spanning flare arcade rooted in a far apart pair of flare ribbons. The second CME is made by eruption of the previously arrested middle flux rope, which blows open the flare arcade of the first CME and produces a flare arcade rooted in a pair of flare ribbons closer to the PIL than those of the first CME. The third CME is made by blowout eruption of the bottom flux rope, which blows open the second flare arcade and makes its own flare arcade and pair of flare ribbons. Flux cancellation observed at the PIL likely triggers the initial confined eruption of the middle flux rope. That confined eruption evidently triggers the first CME eruption. The lid-removal mechanism instigated by the first CME eruption plausibly triggers the second CME eruption. Further lid removal by the second CME eruption plausibly triggers the final CME eruption.

Unified Astronomy Thesaurus concepts: Solar flares (1496); Solar activity (1475); Solar magnetic fields (1503); The Sun (1693); Solar filament eruptions (310); Solar filament eruptions (1981)

Supporting material: animations

1. Introduction

Eruptions of solar filaments/prominences are among the most interesting phenomena that occur on the Sun. Solar filaments are cool and relatively dense plasma material suspended in the hot and relatively tenuous solar corona. Prominences and filaments are the same objects, called filaments when observed against the solar disk and prominences when viewed at the solar limb (see reviews by Labrosse et al. 2010; Mackay et al. 2010; Parenti 2014; Gibson 2018, and references cited therein). According to flux-rope models of filaments and prominences, they are supported by the helical magnetic field of the flux rope (e.g., Filippov et al. 2015, and references cited therein).

Filaments/prominences and flux ropes remain stable in the solar corona through the equilibrium among the upward magnetic pressure, downward magnetic tension, and gravity. They erupt when this equilibrium is disrupted. Various theories/models have been proposed in order to explain the onset of solar eruptions (Forbes 2000; Lin et al. 2003; Schmieder et al. 2013). Three well-known models that have been proposed are “tether-cutting,” “flux cancellation,” and “magnetic breakout” models. The tether-cutting scenario was suggested by Moore & Roumeliotis (1992) and Moore et al. (2001). According to this model, low-lying tether-cutting magnetic reconnection triggers and unleashes the eruption. The low-lying sheared arcade reconnects successively and forms the flux rope. Continuing low-lying reconnection reduces the tension and allows the eruption of the formed flux rope. The flux rope then erupts, and reconnection occurs beneath it. Several observed events have been studied and interpreted using this model (e.g., Liu et al. 2012a, 2013; Joshi et al. 2014, 2015, 2017a, 2017b).

The magnetic breakout model considers a quadrupolar magnetic configuration (Antiochos et al. 1999). According to this model, reconnection at the magnetic null point that lies on top of the middle arcade triggers the eruption of the underlying flux rope. Fast reconnection occurs below the erupting flux rope in the next stage (see Karpen et al. 2012). Various signatures of the breakout model have been observed and interpreted in solar eruptive events (Aulanier et al. 2000; Gary & Moore 2004; Sterling & Moore 2004a, 2004b; Deng et al. 2005; Joshi et al. 2007; Lin et al. 2010; Aurass et al. 2011, 2013; Mitra et al. 2018). According to the flux-emergence model suggested by Chen & Shibata (2000), an emerging bipole within the filament channel cancels with the magnetic field below the filament (or the flux rope) and triggers its eruption. Apart from this, ideal MHD instability has also been investigated to trigger solar eruptions, e.g., by catastrophic loss of equilibrium (e.g., Forbes & Isenberg 1991), kink instability (e.g., Török et al. 2004; Török & Kliem 2005), and torus instability (e.g., Kliem & Török 2006).

Triggering of the eruption of a filament/flux rope by a nearby erupting filament and/or flux rope has also been observed and discussed. Such eruptions are called sympathetic eruptions (Wang et al. 2001, 2007, 2016; Liu et al. 2009; Jiang et al. 2011; Schrijver & Title 2011; Shen et al. 2012; Yang et al. 2012; Joshi et al. 2016b). Wang et al. (2001) studied sympathetic flares and accompanying CMEs from two active regions (ARs), NOAA ARs 8869 and 8872, and discussed the linkage between them through connecting loops. Liu et al. (2009) analyzed successive solar eruptions and CMEs that occurred on 2005 September 13 and found an interrelation among the eruptions. A series of eruptions, coronal mass ejections (CMEs), and related events was observed over 2010
August 1–2 and it was reported that they were connected by a system of separatrices, separators, and quasiparaxial layers (Schrijver & Title 2011). Successive eruptions that occurred on 2003 November 19 have been interpreted as being sympathetic in nature using coronal dimming observations (Jiang et al. 2011). Yang et al. (2012) investigated successive sympathetic eruptions of two filaments in a bipolar helmet streamer magnetic configuration observed on 2005 August 5. In a typical quadrupolar magnetic configuration, Shen et al. (2012) observed sympathetic partial and full eruptions that occurred on 2011 May 12. Recently, Joshi et al. (2016b) studied two successive adjacent filament eruptions and investigated the chain of reconnections during them. Wang et al. (2016) investigated the sympathetic nature of two eruptions that occurred on 2015 March 15 and also noted that the second eruption gave the largest geomagnetic storm of the current solar cycle. Two successive flux rope eruptions and accompanying CMEs that occurred on 2012 January 23 have been studied by several authors (Cheng et al. 2013; Joshi et al. 2013; Sterling et al. 2014). Some sort of magnetic/physical connections between the sympathetic eruptions have been observed in all these studies. For example, Sterling et al. (2014) argued that removal of flux above a filament/flux-rope-carrying nonpotential field arcade can lead to destabilization and eruption of the filament/flux rope, a process they called lid removal. A few attempts to model these kinds of sympathetic eruptions have also been made (see, e.g., Török et al. 2011; Lynch & Edmondson 2013).

The eruption of double-decker filaments, which are composed of two filament branches separated in height, have been observed and studied (Su et al. 2011; Liu et al. 2012b; Cheng et al. 2014b; Ding et al. 2014; Kliem et al. 2014; Zhu & Alexander 2014; Awasthi et al. 2019; Zheng et al. 2019). Liu et al. (2012b) observed the eruption of a double-decker filament having its pre-eruption two branches separated in height by about 13 Mm, and found evidence that transfer of flux and current from the lower branch to the upper branch was the triggering process for the partial eruption of the upper branch (see also Kliem et al. 2014). Zhu & Alexander (2014) studied a similar kind of partial eruption of the upper branch of a double-decker filament that occurred on 2012 May 9. They interpret the eruption in the same way suggested by Liu et al. (2012b).

Several works have investigated an interesting set of multiple eruptions occurring from active region AR 11745. Li & Zhang (2013) studied the dynamics and homologous eruption of four flux ropes from AR 11745 on 2013 May 20–22, in order to understand the characteristics of flux ropes. They observed that these flux ropes erupted consecutively from the AR. Slow flux rope eruption did not produce a CME, while fast eruption did produce a CME. Cheng et al. (2014a) studied the morphological evolution, kinematics, and thermal properties of one of the erupting magnetic flux ropes on 2013 May 22 from AR 11745. For that particular flux rope eruption, they proposed two distinct phases of evolution. In the first phase, the slow-rising phase of the eruption, reconnection occurred within the quasiparaxial layers surrounding the flux rope. In the later phase, the impulsive-acceleration phase of the eruption, fast reconnection occurred underneath the flux rope. The torus instability was found to be responsible for the transition from a slow to fast erupting phase. Mäkelä et al. (2016) studied the source region of type II radio bursts observed on 2013 May 22, and found that the interaction of two CMEs launched from the AR 11745 coincided with the type II emissions. They further recognized that successive eruptions from the same AR produced CME–CME interaction that resulted in solar energetic particle acceleration (see also Ding et al. 2014). None of these studies, however, focused on the triggering process for the successive flux rope eruptions from above the same polarity inversion line (PIL) of AR 11745.

In this work, we revisit the eruption events that occurred in AR 11745 on 2013 May 22, with the motivation of exploring the complex triggering process. We present significant additional results for the triggering processes of these four successive flux rope eruptions from the single PIL of the bipolar AR NOAA AR 11745. The first eruption is of the “confined” variety, during which a filament gets activated and attains quasi-stable height. The three subsequent eruptions are ejective eruptions (blowout eruptions) that each produce a CME. We interpret that the three consecutive successful eruptions are intimately linked with a “triple-decker” flux rope configuration formed in the source region. We focus our study on the cause of onset and the interrelationship among these four eruptions, including evidence that sequential lid removal triggers the second and third CMEs. In Section 2, we describe the observational data set. Section 3 presents the morphology of the AR and the potential-field source-surface (PFSS) extrapolation. The observed onsets and dynamics of the four eruptions and their CMEs are presented in Section 4. Section 5 summarizes the main results and presents an additional discussion.

### 2. Data Set

Data from various instruments are used to study the four consecutive eruptive events. Ultraviolet (UV) and extreme ultraviolet (EUV) images are observed by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012), which is an instrument on board the Solar Dynamics Observatory (SDO;Pesnell et al. 2012). AIA observes the Sun with EUV (304, 131, 171, 193, 211, 335, and 94 Å), UV (1600 and 1700 Å), and white light (4500 Å) channels with a temporal cadence of 12 s, 24 s and 1 hr, respectively and pixel size of 0.6”. Line-of-sight magnetograms with a temporal cadence of 45 s with a pixel size of 0.5” are obtained by SDO’s Helioseismic and Magnetic Imager (HMI;Schou et al. 2012). Full-Sun X-ray flux at 1–8 Å and 0.5–4 Å is observed by the Geostationary Operational Environmental Satellite (GOES). Light curves and images in X-rays for the energy range 3–100 keV are obtained from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI;Lin et al. 2002). For RHESSI X-ray image construction, we use the PIXON algorithm with an integration time of 20 s.

We also use imaging data from the Sun Earth Connection Coronal and Heliospheric Investigation/Extreme Ultraviolet Imager (SECCHI/EUVI), which is an instrument on board the Solar Terrestrial Relations Observatory (STEREO;Wuelser et al. 2004;Howard et al. 2008). It observes the Sun in four wavelengths, 304, 195, 284, and 171 Å, and provides images with 1” pixels. To study the CMEs that accompany the eruptions, we use coronagraph data from STEREO-A/COR1 (Howard et al. 2008) and the Large Angle and Spectrometric Coronagraph (LASCO; Brueckner et al. 1995) on board the Solar and Heliospheric Observatory (SOHO).
3. Morphology of the Active Region and PFSS Extrapolation

Figure 1(a) shows the western half of the Sun in an SDO/AIA 304 Å image at ≈00:00 UT on 2013 May 22. The bipolar active region from which the eruptions originated is shown in the white box in Figure 1(a). As seen, the active region was in the northwest quadrant of the Sun. Figures 1(b) and (c) are zoomed views of the active region in 171 and 4500 Å images. A sunspot can be seen in the 4500 Å image (shown by the white arrow in panel (c)).

Figures 2(a)–(c) show SDO/HMI line-of-sight magnetograms during the period 2013 May 18–22. The magnetic field structure of the active region NOAA AR 11745 is overall bipolar, with leading negative and following positive polarities. There was a large negative-polarity sunspot in this active region. Comparing the HMI images from 2013 May 18 to 22, we see that the overall magnetic structure of the region does not show much change. However, the HMI 720 s line-of-sight magnetogram movie clearly indicates that cancellation is occurring at the main neutral line (see the movie accompanying Figure 2). We have also inspected the HMI SHARP series vector magnetograms, and they are consistent with cancellation occurring at that neutral line. We only display the line-of-sight movie here because the vector movies are of poorer fidelity.

The field structure in the active region’s corona is obtained using the PFSS (Schrijver & De Rosa 2003) extrapolation method. PFSS is an IDL-based algorithm that is available in the SolarSoftWare package (SSW5). The extrapolated magnetic field lines are shown in Figures 2(d)–(e). Figure 2(d) shows a full-disk magnetogram of 2013 May 20 at ≈00:04 UT. Figure 2(e) shows a zoomed view corresponding to the white box area shown in Figure 2(d). From the extrapolation we can

5 http://www.lmsal.com/solarsoft/
see a low-lying arcade, as well as overlying larger coronal-field loops, connecting the negative and positive polarities across the PIL.

4. Dynamic Evolution of the Successive Eruptions

4.1. Investigation of Intensity Profiles

The GOES and RHESSI X-ray temporal flux profiles are shown in Figure 3(a). We can see three events of flux enhancements (marked by I, II, and III in Figure 3(a)) that correspond to three CME-producing eruptive flares. The first event (i.e., event I) is actually a composite of two distinct eruptive events that include an early confined eruption of an activated filament that subsequently triggered the eruption of an overlying flux rope system, causing the first CME. The first event, which starts to rise at $\approx 02:25$ UT, peaks at $\approx 02:56$ UT, and ends at $\approx 03:08$ UT, is a small C1.9-class flare. The second event, which starts at $\approx 06:40$ UT, peaks at $\approx 10:08$ UT, and ends at $\approx 12:00$ UT, is a C2.3-class flare. The third event (which is an M5.0 class flare) starts at $\approx 12:20$ UT, peaks at $\approx 13:32$ UT, and ends at $\approx 23:00$ UT, displaying an extended decay phase. The RHESSI X-ray profiles also show peaks (see colored profiles in Figure 3(a)) that correspond to the peaks in the GOES X-ray profiles during the flares. In the RHESSI X-ray profile, we can observe many large data gaps spanning tens of minutes. These gaps are due periods of RHESSI night or passage through the South Atlantic Anomalous (SAA).

To confirm the source of X-ray flux enhancements during these three eruption episodes, we also made AIA 94 Å time profiles (shown by the solid red line in Figures 3(b)–(c)). Figure 3(b) shows the intensity profile from $\approx 02:00$ UT
to \(\approx 04:30\) UT during the confined-eruption flare, while Figure 3(c) shows the intensity profile from \(\approx 06:00\) UT to \(\approx 16:00\) UT during the flares of the second and third CME eruptions. The area used to calculate the intensity profiles during the first eruption is the field of view (FOV) of Figure 4(c), while for the second and third eruptions the area used is the FOV of Figure 7(a). The average values within these areas are used for these intensity-time profiles. Here we see that the variation in AIA 94 \(\AA\) flux is similar to that of GOES X-ray flux (see AIA and GOES flux profiles in Figures 3(b)–(c)). This confirms that most of the X-ray flux is coming from AR 11745 during these three flare events.

### 4.2. Onset and Progression of the First CME Eruption

The confined eruption that triggers the first CME eruption starts at \(\approx 02:25\) UT, with the activation and confined eruption of an upper strand of the low-lying filament. Figure 4 presents SDO/AIA 335, 131, and 94 \(\AA\) images showing this low-lying activity. The activated filament can be seen very well in AIA 335 \(\AA\)-channel images at \(\approx 02:31\) UT (shown by the arrow in Figure 4(a) and accompanying AIA 335 \(\AA\) movie). In this confined eruption, this low-lying filament flux rope was arrested within the coronal field of the AR, as can be seen in AIA 131 \(\AA\) images (shown by the arrow in Figure 4(b)). The
hot flare loops below the arrested flux rope are also observed in the hot AIA 94 Å channel (see Figure 4(c) and accompanying animation), and are presumably rooted in the inner parts of the two flare ribbons, the parts closely bracketing the PIL (we will refer to these two inner parts of the pair of flare ribbons as R0a and R0b). The ribbons R0a and R0b are pointed to by arrows in Figures 5(d)–(f), and are seen in the AIA 304 and 1600 Å animation accompanying Figures 5. This eruption was faint in other AIA channels. This low-lying activity, we believe, triggered the ejective eruption of an overlying flux rope, even though this low-lying filament eruption remained confined in the coronal field of the AR. The field that overarches the ejective erupting flux rope, and that is blown out by it, can be seen in the SDO/AIA 94 Å running difference movies accompanying Figure 4.

The eruption of the overlying coronal loops can also be seen clearly in STEREO-A/EUVI 195 Å running difference images (shown by the white arrows in Figures 5(a)–(c) and accompanying STEREO EUVI 195 Å movies). STEREO-A EUVI observed this eruption from the west, giving us a different viewing angle. We also observed the brightening in the remote regions (marked by R1a and R1b in Figure 5(d)), which we identify as the flare ribbons made by reconnection below an erupting flux rope. Comparing the ribbons of Figure 5(d) with the line-of-sight photospheric magnetogram (Figure 5(e)), we find that R0a and R1a lie in positive flux, and R0b and R1b lie in negative flux.

The projected height–time plot of this CME eruption using STEREO-A EUVI images is shown in Figure 6(a). The height–time data points are measured along the dashed red line shown in Figure 5(c). To obtain the height–time data points, we trace the visible leading edge of the erupting structure. Three repeated measurements of the height data points have been made to get the average value as well as the errors in the height measurements. The average of these three measurements is the value for each point. The error values in the measurements are the standard deviations of the three height measurements. The linear fit to the height–time points gives us the speed, which comes out to be $\approx 167$ km s$^{-1}$ (see Figure 6(a)).

4.3. Onset and Progression of the Second CME Eruption

The second CME eruption is observed well in the hot SDO/AIA 94 Å channel, as well as in the STEREO-A/EUVI 195 Å channel. A selection of AIA 94 Å images showing the eruption sequence is presented in Figures 7(a)–(c). Eruption of the visible coronal field lines (shown by the dotted arc in Figures 7(a)–(c)) starts at around 07:00 UT, and is observed until 08:15 UT in the AIA FOV (see the SDO/AIA 94 Å intensity and running difference animations accompanying Figure 7). The eruption was also observed by STEREO EUVI from the west. The field-loop blowout eruption is clearly seen in EUVI 195 Å running difference images (see Figures 7(d)–(f) and the animation accompanying Figure 5). The formation of the flare arcade is observed to take place simultaneously with the eruption. The arcade formed just below the erupting structure (see Figures 7(a)–(c)). The flare arcade started forming at $\approx 06:41$ UT. This shows that the flux rope in this eruption already started to erupt before the eruption of the outer loops seen in 94 Å started at $\approx 07:00$ UT. The flare arcade grew in height with time (see Figures 7(a)–(c) and the accompanying animation).

The two feet of the flare arcade are in the two flare ribbons (Figures 8(a)–(b)). Figures 8(a) and (b) display SDO/AIA 304 and 1600 Å images at around $\approx 10:01$ UT, showing the flare ribbons near the western limb. HMI photospheric magnetogram contours (green and blue for positive and negative polarities, respectively) are overplotted onto the SDO/AIA 1600 Å image (Figure 8(b)). The eastward and westward ribbons (marked by R2a and R2b, respectively, in Figures 8(a)–(b)) are in the positive- and negative-polarity regions, respectively. The flare ribbons can also be seen with the STEREO-A EUVI 304 Å channel, viewed from the west (Figure 8(c)). The flare arcade during the late decay phase at $\approx 11:30$ UT can be seen in 304 Å (Figure 8(d)) and 171 Å (Figure 8(e)) of AIA as well as in the STEREO-A EUVI 195 Å (Figure 8(f)).
The height–time profile of the second CME eruption is shown in Figure 6(b). The trajectory along which the height–time data points are obtained is shown in Figure 7(c) with the solid white line. From the AIA 94 Å height–time profile, we observe two steps of evolution: an initial slow eruption with an average speed of around \( \approx 13 \text{ km s}^{-1} \) from \( \approx 06:45 \text{ UT} \) to \( \approx 08:00 \text{ UT} \) (see red line in Figure 6(b)), and a second stage during which it accelerates to \( \approx 56 \text{ km s}^{-1} \) from \( \approx 08:00 \text{ UT} \) to \( \approx 08:15 \text{ UT} \) (see green fitted line in Figure 6(b)). The height–time profile of STEREO EUVI 195 Å shows the same two steps, and gives \( \approx 43 \text{ km s}^{-1} \) for the speed in the second phase (see the orange line in Figure 6(b)). Such two-stage rises in filament trajectories are not uncommon (Sterling & Moore 2005; McCauley et al. 2015; Joshi et al. 2016a; Mitra & Joshi 2019).

### 4.4. Onset and Progression of the Third CME Eruption

The third CME eruption was well observed in almost all EUV channels of AIA. SDO/AIA 94 Å images showing the eruption of the flux rope are presented in Figures 9(a)–(c). This episode starts with a compact brightening near the PIL at around \( \approx 12:13 \text{ UT} \) (shown by the arrow in Figure 9(a)). This brightening is probably due to runaway tether-cutting reconnection between the legs of the low-lying sheared arcade. The flux rope eruption starts at \( \approx 12:13 \text{ UT} \) (Figure 6(c)) and was in its fast-rise phase by \( \approx 12:40 \text{ UT} \) (Figure 6(c)). The compact brightening and the onset of the eruption of the flux rope take place under the second flare arcade (see Figures 9(a)–(c) and the animation accompanying Figure 7). The reconnection takes place below the erupting flux rope between the legs of the enveloping arcade. As a result, the flare arcade is formed.

![Figure 5](URL)
underneath the erupting flux rope and can be seen in Figures 9(d)–(e). We also observed RHESSI X-ray sources at the top of the flare arcade as well as at the feet (see different color contours in the inset of Figure 9(e)). The erupting flux rope can also be seen in STEREO-A EUVI 195 Å running difference image at ≈12:40 UT (Figure 9(f) and the STEREO-A EUVI 195 Å running difference animation accompanying Figure 5). The erupting flux rope blows out the overlying arcade that formed during the second CME eruption (Figure 9(d)).

This eruption produced two parallel flare ribbons seen in AIA (see Figures 10(a)–(b)) and STEREO-A EUVI (see Figure 10(c)) images. The eastern and western ribbons of the flare are marked as R3a and R3b, respectively, in Figures 10(a)–(c). HMI photospheric line-of-sight contours are overplotted on the SDO/AIA 1600 Å image with green (positive) and blue (negative) colors. The eastern and western ribbons lie on the positive and negative-polarity regions, respectively. The flare arcade connecting the two ribbons can be seen at the later time at ≈15:15 UT in AIA 304 Å (Figure 10(d)), 171 Å

Figure 6. Projected height–time profiles of the first (a), second (b), and the third (c) CME eruptions using SDO/AIA as well as the STEREO-A EUVI images. The GOES X-ray profiles of the 1.0–8.0 Å (solid black) and 0.5–4.0 Å (dotted black) channels are also overplotted for comparison. The speeds are estimated by the linear fits to the height–time data points. Error bars are the standard deviations estimated using the three repeated measurements.
Figure 7. (a)–(c) Sequence of selected SDO/AIA 94 Å images showing the second CME eruption and the formation of its flare arcade. The white straight line in panel (c) is the path along which the height–time data points were obtained (see Figures 6(b)). (d)–(f) STEREO-A EUVI 195 Å running difference images, showing the blowing out coronal loops during the second CME eruption. The red line in the panel (f) represents the path along which the projected height points were measured. An animation of the SDO/AIA 94 Å intensity and running difference (not shown in the figure) images of the second and third eruptions from ≈05:30 UT to ≈13:29 UT on 2013 May 22 is available. The realtime duration of the video is 16 s.

(An animation of this figure is available.)

(Figure 10(e)), and STEREO EUVI 195 Å (see Figure 10(f)) images.

4.5. Accompanying CMEs

Figure 11 presents the evolution of three successive CME eruptions, as observed in both STEREO-A COR1 and LASCO C2 and C3 fields of view. A weak CME was made by the first CME eruption (Figures 11(a)–(c)). This first CME appears in the STEREO COR1 FOV at ≈02:55 UT (Figure 11(a)) and in the LASCO C2 field of view at ≈03:15 UT (Figure 11(c)). This first CME only shows a leading-edge structure without a visible CME core. The second and third CMEs on the other hand, show full three-part structure (see Figures 11(d)–(f) and Figures 11(g)–(i), respectively). This is evidence that the second and third CMEs were made by the eruption of flux ropes, which appear as the CME cores in the second and third CMEs (see Figures 11(e) and (i), respectively) The speeds of the first, second, and third CMEs are 244 km s⁻¹, 687 km s⁻¹, and 1466 km s⁻¹, respectively.⁶

5. Results and Discussion

In this work, we analyzed the sequence of four consecutive eruptions that occurred on 2013 May 22 from a single AR, NOAA AR 11745. The active region was overall bipolar with a straight PIL. We interpreted the progression of the eruption sequence using a multiwavelength and multiview data set from

⁶ https://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2013_05/univ2013_05.html
SDO and STEREO-A. The main findings of this work are as follows.

1. Our observations are consistent with the scenario that initially there was a stack of three flux ropes above the PIL of the AR. We call this configuration a “triple-decker” flux rope configuration.
2. The eruption of first (highest) flux rope is triggered by the activation and confined eruption of the middle flux rope, which is an upper strand of a low-lying filament. The confined eruption disturbs the overlying field lines and triggers the CME-producing eruption of the topmost flux rope. The confined eruption made flare ribbons close to the PIL, and the CME eruption produced ribbons far offset from the PIL.
3. The second CME eruption is the blowout eruption of the previously arrested middle flux rope. The removal of overlying flux by the first flux rope’s eruption triggers this second CME-producing flux rope eruption. A large-scale flare arcade and ribbons are also observed to be made by this second eruption.
4. In the third CME eruption the lowest flux rope (carrying the remaining strands of the filament) blows out, followed by the formation of a new flare arcade and flare ribbons.
5. The first CME shows only a faint structure, while the second and third CMEs show a full three-part structure. We presume that there also was an erupting flux rope inside the first CME, although the flux-rope structure of the second and third CMEs is more obvious.
6. The sequential removal of overlying flux (i.e., lid removal; Sterling et al. 2014) during the first and second CME eruptions respectively trigger the second and third CME eruptions. We suppose that the confined first eruption that triggered the first CME was triggered by slow flux-cancellation tether-cutting reconnection at the PIL (Moore & Roumeliotis 1992).

A schematic representation of this sequence of eruptions is shown in Figure 12. In Figure 12(a), the coronal loops from low to high heights are shown by green, red, blue, and black colors respectively, along with flux ropes in between. The first CME eruption is triggered by the activation and confined eruption of upper strands of the filament in the middle flux rope, i.e., flux rope 2 (Figures 12(b) and 4(a)). This confined eruption is plausibly triggered by slow flux-cancellation tether-cutting reconnection at the PIL (Moore & Roumeliotis 1992;
X-ray sources are shown in the inset in panel and drives CME 2 corona for a few hours. It then starts to erupt upward slowly but remains stable at some higher height in the solar Figure 9. The Astrophysical Journal, equilibrium of the topmost

This conduction pair of (innermost conduction) are ribbons denoted as R0a and R0b (Figures 5(d)–(f)). The continued eruption of the topmost flux rope 1 is followed by the reconnection underneath it, heating the farther-separated pair of flare ribbons (R1a and R1b in Figures 12(b) and Figures 5(d)–(e)) and unleashing the first CME (see Figures 12(b) and 11(a)–(c)). At this time flux rope 2 does not erupt, but remains stable at some higher height in the solar corona for a few hours. It then starts to erupt upward slowly and drives CME 2 flare reconnection underneath it between the red field lines (Figures 12(c) and Figures 7). This makes a new pair of flare ribbons (see yellow oval in Figures 12(c)–(d) and Figures 8(a)–(c)) and flare arcade (see Figure 12(d) and Figures 8(d)–(f)). The erupting flux rope 2 drives the second CME (CME2 in Figures 12(d) and Figures 11(d)–(f)). The third CME eruption starts with low-lying runaway tether-cutting reconnection (see the red star in Figure 12(e) and compact brightening in Figure 9(a)). The filament and enveloping flux rope then erupt and drive further flare reconnection underneath.

The ribbons (shown by the yellow colored ovals in Figures 12(e)–(f) and Figures 10(a)–(c)) and the flare arcade (Figures 9(e)–(f) and Figures 10(d)–(f)) form as a result of this reconnection. The erupting flux rope blows out the third CME (CME3 in Figure 12(f) and Figures 11(g)–(i)).

We refer to the stack of three flux ropes above the PIL as a “triple-decker configuration.” To our knowledge, our work here is the first study to propose the presence of this triple-decker magnetic configuration over the PIL of a bipolar AR from observation and analysis. However, earlier there were some studies where the evolution of a double-decker filament system was observed (e.g., Liu et al. 2012b; Kliem et al. 2014; Zhu & Alexander 2014). Those studies suggested two types of double-decker filament configurations: in the first configuration, there is a flux rope above the sheared arcades with dips, while in the second configuration two flux ropes lie stacked over the AR’s PIL, i.e., one over the other (see Figure 12 of Liu et al. 2012b). In our case, i.e., the triple-decker configuration, all three of the flux ropes lie stacked above the AR’s PIL. The formation of flare ribbons and flare arcades across the same PIL after each eruption confirms the presence of this magnetic configuration.

It is important to learn how these typical double-decker and triple-decker flux rope magnetic configurations form. Two mechanisms for the formation of double-decker filaments has see HMI magnetic field animations accompanying Figure 2). This confined eruption of the flux rope 2 filament disturbed the equilibrium of the topmost flux rope 1 and triggered it to erupt (see Figures 12(b) and 5(a)–(c)). Flare reconnection from the confined eruption occurred underneath the erupting flux rope (shown by the lower red star in Figure 12(b)) causing heated innermost flare ribbons denoted as R0a and R0b (Figures 5(d)–(f)). The continued eruption of the topmost flux rope 1 is followed by the reconnection underneath it, heating the farther-separated pair of flare ribbons (R1a and R1b in Figures 12(b) and Figures 5(d)–(e)) and unleashing the first CME (see Figures 12(b) and 11(a)–(c)). At this time flux rope 2 does not erupt, but remains stable at some higher height in the solar corona for a few hours. It then starts to erupt upward slowly and drives CME 2 flare reconnection underneath it between the red field lines (Figures 12(c) and Figures 7). This makes a new pair of flare ribbons (see yellow oval in Figures 12(c)–(d) and Figures 8(a)–(c)) and flare arcade (see Figure 12(d) and Figures 8(d)–(f)). The erupting flux rope 2 drives the second CME (CME2 in Figures 12(d) and Figures 11(d)–(f)). The third CME eruption starts with low-lying runaway tether-cutting reconnection (see the red star in Figure 12(e) and compact brightening in Figure 9(a)). The filament and enveloping flux rope then erupt and drive further flare reconnection underneath.
been discussed by Liu et al. (2012b). In the first possibility the upper branch first forms over the PIL, and the lower branch emerges later to form the double-decker filament system. A possible such emergence of a flux rope under a pre-existing filament has already been observed (Okamoto et al. 2008). In the second possibility, initially both branches of the double-decker filament system reside close together, and later are separated by a partial eruption (Gilbert et al. 2001). In this scenario, the reconnection within the filament flux rope splits the filament flux rope into two branches. In the present study, our observations suggest the presence of a more complex triple-decker flux rope configuration. We speculate that the flux ropes may have formed successively via tether cutting at the PIL. We suppose each flux rope reached some stable coronal height during a confined eruption and remained there until further eruption. In this supposed process, the stack of three flux ropes over one another was formed.

Various mechanisms have been proposed to explain the onset of solar eruptions, e.g., runaway tether cutting (Moore et al. 2001), magnetic breakout (Antiochos et al. 1999), and flux emergence (Chen & Shibata 2000). All these mechanisms are restricted to the erupting field only. In the runaway tether-cutting mechanism the reconnection begins underneath the flux rope, internal to the erupting field. In the breakout scenario the reconnection begins at the top, external to the erupting field. In the flux-emergence reconnection mechanism flux cancellation between existing and emerging nearby field triggers the eruption. The eruption of a double-decker filament due to the interaction and merging between the two branches has been proposed in some studies (Liu et al. 2012b; Kliem et al. 2014; Zhu & Alexander 2014). They suggested that the transfer of mass, magnetic flux, and current from the lower to the upper branch during the interaction is the key mechanism for the upper branch to lose equilibrium. Recently, a new mechanism, referred to as the lid-removal mechanism (Sterling et al. 2014), has been investigated, where it is proposed that the removal of some of the overlying field (blowout of the top of the envelope field) destabilizes the tension–pressure balance in the underlying field. In our case, we observed successive removal of the overlying field during the first and second CME eruptions that apparently triggered the second and third CME eruptions, respectively. Thus, our observations support the lid-removal scenario.

The stability of double-decker filaments using MHD simulation is discussed by Kliem et al. (2014). In their configuration, they considered two vertically arranged force-free flux ropes in a bipolar enveloping external field. In their simulation, they found that the external field’s toroidal (shear)
component is a key parameter controlling the stability of this configuration if the two flux ropes lie close to each other. The double-decker configuration remains stable if the strength of the external toroidal (shear) field is high. In the case where the toroidal component decreases sufficiently, both flux ropes erupt with the initial eruption of the lower flux rope. In the case when the shear field is above a threshold value, the configuration undergoes a partial eruption of the higher flux rope. We also expect that the external magnetic field strength is a key factor for stability or eruption in our triple-decker flux rope configuration. Numerical simulation of such a triple-decker configuration is required to understand more about the stability/eruption conditions in such configurations.

So far, it is unclear how common these types of sequential eruptions from a single bipolar active region may be. The operation of the lid-removal mechanism needs to be modeled in

Figure 11. STEREO-A COR1 (a)–(b) and LASCO C2 (c) images, showing the evolution of the CME made by the first eruption. STEREO-A COR1 (d), LASCO C2 (e) and LASCO C3 (f) images, showing the evolution of the CME made by the second eruption. STEREO-A COR1 (g), LASCO C2 (h), and LASCO C3 (i) images, showing the evolution of the CME made by the third eruption. The LASCO difference images are taken from the LASCO-CME catalog https://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2013_05/univ2013_05.html.
order to understand fully the eruption scenario. Further observational and numerical simulation studies are required to improve our insight into triggering of eruptions by lid removal.

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