FORMATION AND ERUPTION OF A FLUX ROPE FROM THE SIGMOID ACTIVE REGION NOAA 11719 AND ASSOCIATED M6.5 FLARE: A MULTI-WAVELENGTH STUDY

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ABSTRACT

We investigate the formation, activation, and eruption of a flux rope (FR) from the sigmoid active region NOAA 11719 by analyzing E(UV), X-ray, and radio measurements. During the pre-eruption period of ~7 hr, the AIA 94 Å images reveal the emergence of a coronal sigmoid through the interaction between two J-shaped bundles of loops, which proceeds with multiple episodes of coronal loop brightenings and significant variations in the magnetic flux through the photosphere. These observations imply that repetitive magnetic reconnections likely play a key role in the formation of the sigmoidal FR in the corona and also contribute toward sustaining the temperature of the FR higher than that of the ambient coronal structures. Notably, the formation of the sigmoid is associated with the fast morphological evolution of an S-shaped filament channel in the chromosphere. The sigmoid activates toward eruption with the ascent of a large FR in the corona, which is preceded by the decrease in photospheric magnetic flux through the core flaring region, suggesting tether-cutting reconnection as a possible triggering mechanism. The FR eruption results in a two-ribbon M6.5 flare with a prolonged rise phase of ~21 minutes. The flare exhibits significant deviation from the standard flare model in the early rise phase, during which a pair of J-shaped flare ribbons form and apparently exhibit converging motions parallel to the polarity inversion line, which is further confirmed by the motions of hard X-ray footpoint sources. In the later stages, the flare follows the standard flare model and the source region undergoes a complete sigmoid-to-arcade transformation.

Key words: Sun: activity – Sun: filaments, prominences – Sun: flares – Sun: X-rays, gamma rays

Supporting material: animation

1. INTRODUCTION

Coronal mass ejections (CMEs) affect space weather phenomena immensely. Thus a major objective of research in solar physics in recent times has been to explore the characteristics of the source region of CMEs. Through these efforts, some conditions have been recognized that are favorable for eruptions. In this regard, the appearance of a “sigmoid” in the active region corona is considered to be an important precursor of CMEs. It is widely accepted that sheared and twisted coronal fields associated with sigmoids can store a large amount of free magnetic energy, which is ultimately released during the CME.

Sigmoids were first identified by the Yohkoh Soft X-ray Telescope (SXT) as large regions producing enhanced soft X-ray emission and having S-shaped (or inverse S-shaped) morphology (Manoharan et al. 1996; Pevtsov et al. 1996; Rust & Kumar 1996; Sterling & Hudson 1997; Moore et al. 2001). Using SXT data, Hudson et al. (1998) studied the source region of several halo CMEs and found that, for the majority of events, the source region exhibited a characteristic pattern in which pre-eruption sigmoids turned into loop arcades following the passage of a CME (see also Sterling et al. 2000). Using a large data set of SXT images, Canfield et al. (1999) classified solar active regions into sigmoidal and non-sigmoidal categories and found that activity centers of the former type are more likely to be eruptive than the others. Sigmoids can be classified into two groups according to their morphology and timescale of evolution: transient and persistent (Gibson et al. 2006). Transient sigmoids brighten up for only a short period of time, usually just before the eruption (see, e.g., Pevtsov et al. 1996). They tend to be more well defined in the form of apparently a single, sigmoid loop. Notably, observations reveal that many sigmoids have the shape of two J’s or elbows, which together form the S-shape of the sigmoid (see, e.g., Moore et al. 2001). Persistent sigmoids present much intricate morphology in which many discrete sheared loops collectively form a sigmoidal structure. They are long-lived features that last for a considerably longer time than transient sigmoids (from days to weeks) (see, e.g., McKenzie & Canfield 2008).

Underneath the twisted coronal soft X-ray (SXR) structures, filament channels are frequently observed in Hα observations (Pevtsov et al. 1996; Gibson et al. 2002; Pevtsov 2002). Although the evolution from sigmoid to arcade is quite dramatic, the underlying filament may or may not show significant changes with the sigmoid eruption (Pevtsov 2002). Further, sigmoids can also develop over decayed active regions that show a weak and dispersed distribution of magnetic flux (Glover et al. 2001). We believe that there is some coupling between these two structures (sigmoid and filament) although observations in these two channels (SXR and Hα) correspond to the hottest and the coldest material associated with the sigmoidal regions. Therefore, it is essential to probe what happens in between these two layers and temperature regions during the formation and disruption stages of the sigmoids. This objective can be accomplished by analyzing suitable multi-wavelength data sets. Recent studies indicate that sigmoidal structures are visible over a wider range of
temperature (Liu et al. 2007). Finally, we need to understand how the overlying coronal and chromospheric structures are related to the underlying magnetic field evolution through the photosphere.

The emergence or formation of magnetic flux ropes (FRs) in solar active regions and their subsequent eruption has been recognized as the key component in the process of evolution from sigmoid to arcade (see, e.g., Titov & Démoulin 1999; Kliem et al. 2004; Archontis et al. 2009; Chatterjee & Fan 2013; Schmieder et al. 2015; Jiang & Feng 2016; Kumar et al. 2016). Contemporary observations, taken from multiple EUV channels of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO), indeed provide evidence for the existence and activation of the hot FR in the active region corona (see, e.g., Cheng et al. 2011, 2013a; Chen et al. 2014; Kumar & Cho 2014; Cheng & Ding 2016). Further, the comparison between the kinematic evolution of the FR and associated CME reveals that the hot FR acts as the earliest signature of the CME (Cheng et al. 2013b, 2014a).

In this study, we present a comprehensive multi-wavelength analysis of the morphological evolution and eruption of the sigmoidal active region NOAA 11719 on 2013 April 11. We discuss the dramatic evolution of this active region over a period of nine hours (00:00–09:00 UT). In this period, an EUV sigmoid structure emerged through the interactions between two J-shaped bundles of loops that involve multiple events of localized energy release and photospheric flux changes. Subsequently, we observe the ascent and eruption of an FR from this sigmoidal region. This study is preliminary, based on multi-channel E(UV) imaging taken from the AIA (Lemen et al. 2012) with unprecedented spatial and temporal resolutions. Notably, the evolution of the sigmoid was observed in AIA 94 Å images, which implies that the structure was composed of plasma at very high temperature (∼6 MK). During the eruption, we observed a large M6.5 flare (SOL2013-04-11), which is characterized by a prolonged SXR rise phase of ∼21 minutes. It is striking that the evolution of the flare during the early rise phase deviates significantly from the standard flare model. The Hα observations from Kanzelhöhe Observatory (KSO; Pötzi et al. 2015) revealed that a long active region filament existed below the coronal sigmoid, which partially erupted during the M6.5 flare and caused a large two-ribbon flare in the chromosphere. The temporal and spatial evolution of hard X-ray (HXR) emission during the M6.5 flare was studied using multi-band X-ray time profiles and images obtained from RHESSI (Lin et al. 2002). A detailed comparison of chromospheric and coronal activities during the evolution of the sigmoid with the changes in photospheric magnetic flux was undertaken to investigate the triggering mechanism involved in this eruption. For magnetic field measurements, we have analyzed longitudinal magnetograms from the Helioseismic Magnetic Imager (HMI; Schou et al. 2012) on board SDO. These multi-wavelength observations are further supplemented by radio dynamic spectra obtained from the HiRAD radio spectograph. We present an observational overview of the activities in Section 2. The analysis and observational results are presented in Section 3. We interpret our results and emphasize the uniqueness of this work in Section 4. A summary of this study is given in Section 5.

2. OVERVIEW OF OBSERVATIONS

In Figure 1, we present a multi-wavelength view of the active region NOAA 11719 at white light (WL), 94 Å, and Hα wavelengths to show the distribution of sunspots and associated coronal features. The WL image clearly indicates that the active region (AR) consists of several sunspots of small to intermediate size, with the largest one possessing negative polarity (see Figures 1(a) and (b)). It is interesting to note that most of the prominent sunspots are of negative polarity. Further, there is a scarcity of sunspots exhibiting positive polarity while the positive flux region is dispersed over a larger area (Figure 1(b)). The overall photospheric flux distribution suggests a βγ magnetic configuration of the AR. An inverse S-shaped structure (i.e., a sigmoid) is observed in the AIA 94 Å images, which consists of a set of highly sheared coronal loops (Figure 1(c)). From Hα filtergrams of the active region, we find that a long filament channel exists under the coronal sigmoid, which is indicated by arrows in Figure 1(d). We observed significant variations of magnetic flux in AR 11719 from several hours prior to the eruption until the post-eruption phase (∼00:00–10:00 UT). During the eruption of the FR, a large M6.5 two-ribbon flare was observed at the location N09E12 together with an associated halo CME. According to the GOES 1–8 Å flux, the flare started at 06:55 UT, reached its maximum at 07:16 UT, and ended at 7:29 UT.

3. ANALYSIS AND RESULTS

3.1. Pre-eruption Activities

Pre-eruption activities refer to the processes leading to formation and activation of the EUV sigmoid that subsequently erupts during the M6.5 eruptive flare. The evolution of the sigmoid in the pre-eruption phase is illustrated in Figure 2 by a sequence of AIA 94 Å images. The AIA 94 Å channel (Fe XVIII; log(T) = 6.8) is apt for the understanding of structures associated with high plasma temperature in the hot flaring corona. In the beginning (∼00:00 UT), two nearby bundles of coronal loops are identified (marked by arrows in Figure 2(a)). At this stage, we cannot clearly identify connectivity between these loops. From ∼1:40 UT, the intensity of the two loop systems increases and we clearly notice the establishment of connectivity between them in a sequential manner. This phase (∼1:40–2:00 UT) is characterized by a build-up of bright, diffuse emission in the region that lies between the two loop systems. The coupled loop system undergoes further expansion and the whole region evolves into a large coronal sigmoid at ∼04:30 UT (see Figure 2(h)). Further, during formation of the sigmoid, the western part of the active region remains active in the form of continued episodic brightening and diffuse emission (shown inside the dotted box in Figure 2(c)). This region is densely occupied by a cluster of low-lying loops.

It is striking to note the successive emergence of coronal loops in a region that lies between two J-shaped bundles of loops (indicated by arrows in Figures 2(f)–(g)). Further, the loops in this region brighten up several times (∼3:00–3:15 UT, ∼3:55–4:10 UT, ∼4:30–4:40 UT) until the sigmoid structure is fully developed. It is noteworthy that the two J-shaped bundles of loops transform successively into a coherent sigmoid
structure via transient loop brightenings that occur between them.

Finally, we highlight the rise of a large bundle of FRs that evolved into a kinked structure toward the southeast side of the sigmoid (see the region inside the dotted box in Figure 2(k)). We clearly notice that the top portion of this FR exhibits writhing motions with the simultaneous expansion of its legs, during which the core of the sigmoid brightens up at multiple locations (∼6:30 UT). We further mention the rise of another thread of this FR from the eastern leg of the sigmoid. These rising structures clearly reveal the slow yet steady expansion of a hot FR well before the onset of the impulsive flare emission (see Figure 2(l)).

3.1.2. Episodic Energy Release in the Vicinity of the Filament Channel

In Figure 3, we present a sequence of AIA 304 Å images of the AR showing the incidences of episodic brightenings in the vicinity of a long filament channel during the pre-eruption phase (i.e., between 00:30 UT and 06:00 UT). The AIA 304 Å channel (He II; log(T) = 4.7) images the solar structures formed at the chromosphere and the transition region. In Figure 4, we provide composites of the AIA 94 Å and 304 Å images. These images reveal good spatial correlation between the filament channel and overlying hot coronal sigmoid. The AIA 304 Å images reveal interesting evolutionary stages of the filament channels. At the very beginning (i.e., at ∼00:28 UT), we observed a U-shaped filament in the southwest part of the AR with localized brightening at its southern side (marked by an arrow in Figure 3(b)). Thereafter, we note episodic brightenings from various portions of the filament channel (marked by arrows in Figures 3(d)–(h)) and a simultaneous extension in the length of filament toward the northeast part of the AR. A small portion of the filament, situated at its northern side, undergoes confined eruption and is associated with an intense EUV brightening at ∼03:05 UT (marked by an arrow in Figure 3(i)). At around 03:40 UT, the filament channel attains its maximum length and a clear S-shaped structure emerges (see Figure 3(l)), which is the chromospheric counterpart of the coronal sigmoid seen in AIA 94 Å images (Section 3.1.1). After complete development of the filament, its eastern part started to lift up and it partially disrupted in next few minutes. At this stage, we observed ribbon-like brightenings below the rising portion of the
Figure 2. Series of AIA 94 Å images showing the development of the sigmoidal structure in active region NOAA 11719 during the pre-eruption phase. Note the ascent of the flux rope (FR) from the active region (marked with a dotted-box region and arrows in panels (k) and (l), respectively).
filament (see Figure 3(m)). However, the southwest portion of the filament has remained quiet.

3.2. Evolution of Magnetic Flux

It is well established that the coronal transients are driven by the solar magnetic fields (e.g., reviews by Priest & Forbes 2002; Schrijver 2009; Wiegelmann et al. 2014). Therefore, it is crucial to explore how the photospheric magnetic flux evolves prior to and during the eruptive phenomena. In Figure 5(a), we overplot an HMI magnetogram (as contours) displaying the distribution of photospheric line-of-sight magnetic fields on the AIA 94 Å image showing the coronal sigmoid. We have selected the following two regions on the HMI magnetogram to investigate the evolution of magnetic flux during the sigmoid-to-arcade transformation: (1) the large region that encompasses

Figure 3. Series of AIA 304 Å images showing the occurrence of sequential brightenings (indicated by arrows) from different locations of a long filament channel. The emergence of an S-shaped filament can be clearly seen in panel (l), where the relatively straight middle part along with hook-shaped eastern and western portions are indicated by arrows.
the whole sigmoid (see the region defined within the rectangular box in Figure 5(a)), and (2) the smaller region that forms the central part of the sigmoid (enclosed by a curve in Figure 5(a)). This central region is of particular interest because transient loop brightenings occurred continuously in this region, during which the two J-like bundles of loops successively transformed into the sigmoid (discussed in Section 3.1.1; also see Figures 2(f) and (g)). Notably, during the M6.5 flare, the HXR footpoint emission also occurs within this region, implying this to be the core region associated with magnetic field lines involved in the large-scale magnetic reconnection process (see Section 3.3). The positive and negative flux through the extended activity site and the smaller core region are plotted in Figures 5(b) and (c), respectively. HMI provides the line-of-sight magnetogram at a cadence of 45 s with a spatial resolution of 0.5 arcsec. The line-of-sight magnetograms for 10 hr starting from 00:00 UT on 2013 April 11. The magnetograms are differentially rotated to a common heliographic location and corrected for the line-of-sight effect by multiplying by 1/\cos(\theta), where \theta is the heliocentric angle. We averaged four magnetograms to reduce the noise level. For a comparison between the evolution of magnetic flux and the coronal energy release, we plot the GOES 1.0–8.0 and 0.5–4.0 Å flux in Figure 5(d).

We find that the photospheric magnetic fluxes of positive and negative polarities undergo a continuous increase within the sigmoidal active region during the pre-eruption phase, i.e., 00:00 UT to 06:55 UT (Figure 5(b)). Notably, this whole duration is characterized by significant coronal activities in the forms of localized episodes of energy release and evolution of bright loops from the EUV sigmoidal region. Further, we note that the positive flux continues to rise following the flare onset at 06:55 UT while the negative flux maintains an almost steady level from \sim 05:20 UT until the decay of flare emission at \sim 07:30 UT. More interesting variations of magnetic flux are observed in the core region (Figure 5(c)). The negative flux undergoes a slow rise until \sim 05:20 UT while the positive flux exhibits both increasing and decreasing episodes. In the later phases (>05:20 UT), the negative flux, in general, decreases. Interestingly, the rate of decrease of negative flux is higher during the rise phase of the M6.5 flare. On the other hand, the evolution of positive flux is rather striking. We note that the positive flux decreases during the pre-flare period (\sim 05:20–06:40 UT). However, it changes its trend completely with the onset of the M6.5 flare and starts to increase.

3.3. The Eruptive M6.5 Flare

3.3.1. Flare Light Curves

After significant pre-eruption activities in the forms of photospheric magnetic changes, the formation, evolution, and activation of a long filament channel, and localized brightenings from various locations close to the filament channel, a large M6.5 flare occurred in AR 11719, which is associated with a fast halo CME. In Figure 6, we present the flare light curves in multiple X-ray energy channels from 06:45 to 07:45 UT on 2013 April 11. The GOES SXR profiles presented in Figure 6 clearly indicate the onset of flare emission at \sim 06:55 UT, while gradually declining SXR flux lasted until after 7:40 UT. It is important to note a rather prolonged rise phase of
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3.3.2. Sigmoid-to-Arcade Evolution

In Figure 7, we present series of AIA 94 Å images to show the sequential evolution of the sigmoid into the post-flare arcade during various phases of the energy release in the M6.5 flare. The RHESSI HXR contours in different energy bands (12–25 keV; yellow, 25–50 keV; red, and 50–100 keV; blue) are also overplotted on selected EUV images. We recall that the FR ascends from ~06:00 UT, i.e., about an hour before the onset of the M6.5 flare (Section 3.1.1). We note that the rising FR remained in a quasi-stationary state for several minutes (~6:30–6:55 UT) before undergoing rapid expansion from ~6:55 UT, which marks the impulsive rise of the flare emission (Figures 6 and 7). With the rapid eruption of the FR, we observe intense brightenings in the source region, which subsequently evolved into two distinct flare ribbons. The co-temporal AIA 94 Å and RHESSI HXR images reveal that the high-energy emission is entirely associated with the middle portion of the EUV sigmoid. Further HXR emission originates in the form of kernels that lie over conjugate EUV flare ribbons. Following the peak phase of SXR emission (~7:16 UT; Figure 6), a beautiful system of post-flare arcades envelops the flaring region (Figure 7(b)) that was occupied with the sigmoid in the pre-eruption phase. In Figure 8, we present a few representative AIA 131 Å images of the activity site. The AIA 131 Å channel (Fe VIII, XXI; log(T) = 5.6, 7.0) observes plasma structures in the transition region and the flaring corona. From these images, we clearly notice that, following the eruption of the FR, a cusp forms at the apex of hot EUV loops (marked by an arrow in Figure 8(c)).

3.3.3. Early Rise Phase and Deviation from the Standard Flare Model

From the X-ray and EUV flux profiles, it is evident that the event under study belongs to the category of long-duration events, which are marked by the typical evolution of long, parallel flare ribbons in the chromosphere. However, during the prolonged rise phase of this flare with a duration of ~21 minutes (Figure 6), the flare ribbons and associated HXR sources exhibit a complicated dynamical evolution. For the detailed study of the evolution of flare ribbons, we have presented a sequence of KSO Hα and AIA 1600 Å UV images in Figure 9. The sequence of Hα filtergrams provides information about the flare morphology in the chromosphere and the response of phenomena releasing coronal energy in this layer. The AIA 1600 Å channel (C IV + cont.; log(T) = 5.0) observes combined emission from the transition region and the upper photosphere. The co-temporal HXR contours in 25–50 keV (red) are also overplotted on a few representative Hα images (Figures 9(c), (e)–(g)).

The early Hα flare emissions originate in the form of bright kernels (see Figures 9(a) and (b)) that subsequently evolve into the flare ribbons (marked as the eastern and western flare ribbons in Figure 9(b)). It is important to note that the flare ribbons exhibit a J-shaped structure during the early stages (Figures 9(b)–(f)). In particular, this J-shaped morphology is quite prominent for the eastern flare ribbon, which is also larger and undergoes more dynamic evolution during the early rise phase of the flare (i.e., between 06:55 and 07:06 UT). A comparison of Hα filtergrams with the evolution of the sigmoid seen in AIA 94 Å images (see Figures 7 and 9) suggests that the hooked part of the J-shape for the eastern flare ribbon is associated and probably physically linked with the eruption of the eastern portion of the overlying FR. On the other hand, the western flare ribbon is shorter and exhibits a simple morphology. We note that the HXR conjugate sources in the 25–50 keV energy bands nicely correlate with the brightest part of the respective Hα flare ribbons (see Figures 9(c), (e)–(g)). In Figures 9(d) and (i), we have overplotted HMI magnetograms on the co-temporal Hα and UV images, respectively, to compare the evolution of flare ribbons with respect to photospheric magnetic polarities. It is noteworthy that the Hα filament nicely delineates the separation of
opposite magnetic polarities in the photosphere and, therefore, can be considered to approximately outline the polarity inversion line (PIL). Both Hα and UV images clearly reveal that the eastern flare ribbon extends in the southwest direction, parallel to the PIL until \( \sim 7:06 \) UT, while the western flare ribbon evolves in the opposite direction. The spatial evolution of flare ribbons observed during the early rise phase is not consistent with the canonical picture of eruptive two-ribbon flares. In particular, the conjugate J-shaped flare ribbons apparently move toward each other parallel to the PIL.

To compare the evolution of low- and high-energy X-ray-emitting regions, we have shown a sequence of RHESSI 6–12 keV images (gray background) overlaid by co-temporal 25–50 keV (yellow contours) in Figure 10. As described earlier, we observed two distinct HXR sources (marked as FP-east and FP-west in Figure 10(b)). Due to the limited observations from RHESSI, we could investigate the motion of HXR sources only during the initial \( \sim 6 \) minutes of the rise phase. We find that the separation between conjugate HXR sources decreases in the successive images, further confirming the observed converging motions of flare ribbons (see also Figures 9(c), (e)–(g)). We also note that initially FP-west is relatively weak and does not show much spatial variation. On the other hand, FP-east is stronger and moves toward FP-west. Further, the intensity of FP-west increases with the rise phase and becomes comparable to that of FP-east by \( \sim 07:02 \) UT (see Figures 10(e) and (f)). Also by this time, the two FP sources come closest to each other and their corresponding flare ribbons have become almost parallel (see Figure 9(n)). The 6–12 keV X-ray source exhibits a single

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**Figure 7.** Sequence of AIA 94 Å images showing expansion and eruption of the flux rope (FR) during the M6.5 flare. Co-temporal RHESSI HXR sources in 12–25 keV (yellow), 25–50 keV (red), and 50–100 keV (blue) are also overplotted on the representative AIA 94 Å images (panels (c)–(e)). A bright post-flare loop arcade is formed after eruption of the flux rope (see panels (f)–(h)). RHESSI images are reconstructed with the CLEAN algorithm with an integration time of 1 minute. The contour levels are set as 50%, 70%, and 90% of the peak flux in each image. (An animation of AIA 94 Å observations is available online showing eruption of the flux rope from the sigmoidal active region.)

(An animation of this figure is available.)
structure and moves slowly toward the southwest during the rise phase.

3.3.4. Standard Phase of the Eruptive Flare

The early rise phase (06:55–07:06 UT; see previous section) is characterized by the converging motions of flare ribbons. In the subsequent stages, we note the “standard” evolution of a pair of well developed, classical flare ribbons, during which they apparently move away from each other in the direction perpendicular to the PIL. To show the standard phase of the M6.5 flare, we present KSO Hα, AIA 1600 Å, and AIA 304 Å images in Figure 11. We note that, of the two ribbons, the eastern one undergoes more dynamic evolution and lateral expansion than the western flare ribbon (Figure 11). Notably, the eastern flare ribbon remains prolonged and bright until the late gradual phase of the event while the western flare ribbon decays appreciably in length as well as intensity of the emission. In this context, we emphasize that the western ribbon is associated with stronger magnetic field (negative polarity) while the eastern ribbon forms over the weaker and dispersed flux regions (positive polarity) in the photosphere (Figure 11(g)). These observations indicate crucial evidence for the asymmetric distribution in the injection of accelerated particles into the flare loop systems.

3.4. CME Observations

The eruption of the FR eventually leads to an Earth-directed (halo) CME. In Figure 12, we show a few representative WL images observed by LASCO on board SOHO. The CME was first seen in the field of view of coronagraph C2 at 07:24 UT at a position angle of 85°. The halo structure of the CME emerged after 07:46 UT in C2, and was tracked by coronagraph C3 until 12:00 UT up to a height of 24 Rs. The height–time plot available at the SOHO LASCO CME catalog5 shows that the linear speed of the CME is ≈860 km s⁻¹. Here it should be noted that the CME originated almost in the center of the disk, and thus its linear speed should be considered to be its expansion speed. A second-order fit to the height–time data indicates a deceleration of ≈8 m s⁻² in the propagation of the CME. Here it is worth mentioning that the coronagraph COR1 on board SECCHI/STEREO-B, which observes the inner corona (1.5–4 Rs.; Howard et al. 2008) with better temporal resolution (5 minutes), detected this CME at ~07:10 UT when the M6.5 flare was still going through its rise phase (Figure 6). The early detection of the CME is due to the different viewing angle of STEREO-B with a separation angle of 142° from Earth (in heliocentric coordinates) on the day of observation.

3.5. Dynamic Radio Spectrum

The HiRAS spectrograph6 operated by the NICT, Japan, observed significant activities over a wide range of frequencies between 30 and 2000 MHz in association with this sigmoid eruption. We present the HiRAS spectrum in Figure 13. At high frequencies in the spectrum (~1800–600 MHz), we observe type IV continuum emission from the early rise (~06:55 UT) to the peak phase of the flare (~07:16 UT). It is remarkable to note three prominent patches of type IV continua at the beginning (~06:55–07:08 UT; marked by arrows in Figure 13). Notably, this interval correlates with the early rise phase of the flare (see Section 3.3.3). At this time, the eruption initiates from the sigmoid with the expansion of the FR (see Figures 7(a) and (b)). The first patch is the most intense (~06:55–07:01) and forms within the frequency range ~1800–600 MHz, showing it to be situated at very low coronal heights. We find a gradual decrease in the intensity as well as a drift of frequencies toward the lower side for the successive type IV continua, which implies the continuous bulging of coronal loop systems associated with the sigmoid during the rise phase. It is noteworthy that, during the period of early type IV emission, we also observe a number of type III radio bursts (~06:55–07:01 UT) in a much lower frequency region of the spectrum (from ~50 to 50 MHz).

The rise phase of the M6.5 flare is further characterized by an intense and broad type II radio burst during ~07:01–07:14 UT (see the region between the vertical dashed lines in Figure 13). However, the weak emission from this burst can be seen up to 07:20 UT. It may be noted that the type II emission starts at a frequency of ~165 MHz at ~07:02 UT and extends down to ~35 MHz at ~07:14 UT. However, the spectrogram clearly reveals the fundamental emission of this burst running parallel to the above intense burst in a lower frequency range. Using the coronal density model of Newkirk (1961), we estimate the heliocentric height of the type II burst to be ~1.5–2.6 Rs, which corresponds to a speed of ~1090 km s⁻¹. A comparison of the

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5. http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/2013_04/univ2013_04.html

6. http://sunbase.nict.go.jp/solar/denpa/index.html
evolution of the sigmoid observed in the AIA 94 Å images (Section 3.1.1) with the radio dynamic spectrum provides more insights into the evolutionary stages associated with the FR expansion. It is likely that the rapid expansion of the EUV FR would induce magnetic reconnection in the stretched overlying magnetic field lines. The electron beams escaping from the reconnection region would thus provide radio signatures in the form of type III radio bursts. The subsequent type II radio

Figure 9. (a)–(h) KSO Hα and (i)–(p) AIA 1600 Å images showing the temporal evolution of flare brightenings/ribbons during the early rise phase (i.e., 06:55–07:05 UT; see Figure 6). During this early phase, the flare ribbons present a J-shaped morphology and show lateral extension toward each other. Note that by the end of this early phase (∼07:05 UT), the flare ribbons become parallel to each other, and they exhibit "standard" morphology and spatial evolution thereafter. The eastern and western ribbons are indicated by arrows in panel (b). The co-temporal HXR contours in the 25–50 keV (red) energy band are overplotted on a few representative Hα images (panels (c), (e)–(g)). In panels (d) and (i), the contours represent the distribution of magnetic polarity (blue: negative, red: positive) over Hα and AIA 1600 Å images respectively. RHESSI images are reconstructed with the PIXON algorithm with an integration time of 1 minute. The contour levels are set as 10%, 20%, 40%, and 80% of the peak flux in each image.
emission implies propagation of the shock wave resulting from the eruptive expansion of the associated FR–CME system.

4. DISCUSSIONS

In this paper, we present a multi-wavelength investigation of a sigmoid-to-arcade development in AR 11719 on 2013 April 11. The study aims to explore several crucial aspects involved during the process of a solar eruption right from the pre-eruption stages of a coronal EUV sigmoid to the post-flare phase. We further provide valuable insights about the physical processes occurring simultaneously in different layers of the solar atmosphere during the successive transformation of hot active region loops into the sigmoid that continued over several hours (~7 hr) prior to the eruption.

4.1. Formation and Activation of the Sigmoid

The comprehensive analysis of AIA EUV/UV images and HMI magnetograms of about 9 hr duration was undertaken to explore the formation and eruption of the sigmoid and its association with the basic process of the evolution of magnetic flux through the photosphere. The simultaneous observations of the active region in hot (94 Å; \( T \sim 6 \text{ MK} \)) and cool (304 Å; \( T \sim 50,000 \text{ K} \)) channels clearly reveal that the formation of the sigmoid occurred in multiple steps. The EUV observations at 94 Å reveal two pre-existing J-shaped coronal loop systems that successively transformed into a sigmoid structure. Coronal sigmoids were discovered in SXR emission as a precursor to CMEs (Manoharan et al. 1996; Rust & Kumar 1996). However, many recent studies have confirmed that sigmoid structures can be observed in different EUV channels, which provides evidence that sigmoids exist over a wider range of temperatures (Liu et al. 2007; Cheng et al. 2014b). Our study reveals that transient and localized brightenings, associated with the successive emergence of hot loops, proceed in the region between the two J-shaped loop bundles as they appear to coalesce and a coherent sigmoid structure evolves (Figure 2), which provides evidence of the role of magnetic reconnection in the formation of the sigmoid. With the complete development of the sigmoid, its extended middle section along with the elbow regions on each side produce intense emission in the AIA 94 Å images. This implies that the twisted structure is at a higher temperature (\( T \sim 6 \text{ MK} \)) than the ambient active region corona.

The phase of sigmoid formation in the corona is associated with dynamical activities in lower layers of the solar...
atmosphere, namely, the chromosphere and transition region. We observe multiple brightenings at different locations of the filament channel that was observed in 304 Å images. A large brightening occurred prior to the merging of two filament channels, and the coupled structure undergoes continuous rapid evolution (Figures 3(i)–(k)). Following multiple, localized releases of energy at different locations, an S-shaped long channel emerged that essentially represents the core region of the overlying EUV sigmoid. The study reveals simultaneous changes in the configuration of overlying as well as core regions during the formation of the sigmoid. The association between the twisted filament structures and overlying coronal sigmoid has been recognized in several studies (Pevtsov et al. 1996; Gibson & Low 2000; Gibson et al. 2002; Pevtsov 2002). In all these papers, the filament was studied in Hα. Pevtsov (2002) studied a set of active region filaments associated with an X-ray sigmoid. This study reveals that, as the eruption proceeds, the sigmoid gets replaced by a cusp or arcade, while the underlying Hα filament does not show significant changes. In comparison to the study of Pevtsov (2002), where evolution of the filament was studied following the onset of eruption, we have studied the morphological changes in the filament during the formation as well as eruption of the sigmoid. Further, in our study, the evolution of the filament is studied in EUV images at 304 Å, which observes structures in the transition region and chromosphere that are formed at a higher temperatures than Hα features. From these observations, we infer that the chromosphere and its overlying transition region containing dense filament material were highly dynamic when various coronal activities (observed in the 94 Å channel) occurred as the sigmoid was taking its shape. This also suggests that perhaps multiple, localized brightenings in the corona and lower layers are associated with magnetic reconnection at the height of the chromosphere and/or transition region. Vemareddy & Zhang (2014) found that the heating and localized brightenings during the activation of the flux rope result in significant increases in the emission measure, density, and temperature of the coronal region, supporting the reconnection scenario. Complementary to these results, Cheng et al. (2015) provide evidence from spectroscopic observations from the Interface Region Imaging Spectrograph (De Pontieu et al. 2014) that support the role of magnetic reconnection in
the formation of magnetic flux ropes. In their study, the signatures of magnetic reconnection were observed in the form of red/blue shifts along with non-thermal broadenings at the footpoints of magnetic flux ropes.

Significant variations in photospheric magnetic flux were observed within the sigmoidal region right from its formation stages (Figure 5(b)). There was a continuous increase in both positive and negative flux when the whole sigmoidal region is considered (Figure 5(b)). By combining EUV and magnetogram observations, we propose a scenario in which multiple magnetic reconnections, revealed by localized, transient brightenings, occur continuously at lower coronal heights with a general increase in photospheric magnetic flux. It is noteworthy that the role of flux emergence toward the build-up of complexity in sigmoids has been recognized in simulations (Archontis et al. 2009). In this model, continual flux emergence would proceed with the formation of the flux rope through internal reconnections. Thus, the loops that form the overall sigmoid are reconnected field lines heated by reconnection along the current layers. Our observations indicate that the localized, multiple reconnection events, mainly occurring within the core region, have not only reconfigured the magnetic topology of the region toward the formation of the large sigmoid but also contributed in sustaining the temperature of the sigmoidal FR at a higher level than the ambient corona.

Although our observations show significant flux emergence during the formation of the FR, this may not be common to all the events. For example, Cheng et al. (2014b) found no significant flux emergence in the period of magnetic FR formation. On the other hand, some studies, pertaining to the long-term evolution of active regions, have shown significant flux cancellation along the PIL over a longer timescale (~2.5 –3.5 days) during the process of flux rope formation (Green et al. 2011; Yardley et al. 2016).

More striking variations of the photospheric magnetic flux were observed from the core field region associated with the eruption of the flux rope and the subsequent M-class flare (see the region enclosed by the curve in Figure 5(a) and corresponding flux plots in Figure 5(c)). The investigation of flux profiles through this region reveals an increase in negative flux until 05:20 UT. More interestingly, the positive polarity undergoes episodes of increasing as well as decreasing flux evolution. It is worth recalling that during this interval the core region exhibited episodic brightenings characterized by the emergence of a bright loop system. Following each such event, the two J-like bundles of loops successively transform into a more coherent sigmoid structure (Figure 2).

It is important to note that the flux rope activation has temporal and spatial consistency with the flux cancellation through the core region that started ~1.5 hr before the M6.5 flare (time indicated in
4.2. The M6.5 Flare and Sigmoid-to-Arcade Transformation

The M6.5 flare underwent a very prolonged rise phase of \(~21\) minutes, which is significantly longer than the median rise time of \(10\) minutes for M-class flares (Veronig et al.

The rise phase is characterized by a gradual build-up of the SXR flux between \(06:55\) and \(07:16\) UT (Figure 6). A careful analysis of imaging observations in EUV, Hα, and HXR channels reveals that the rise phase exhibits a complex dynamical evolution of flare ribbons and HXR footpoints during its early stages. In view of this, we have divided the rise phase of the flare into two parts: early rise phase \((06:55-07:06\) UT) and late rise phase \((07:06-07:16\) UT). The fundamental difference between these phases lies in the fact that the emission signatures of the early rise phase do not comply with the scenario of the standard flare model while the late rise phase correlates well with the criteria of the standard flare (see, e.g., Joshi et al.

Although a flare with prolonged rise phase is a subject of interest in itself, it is not an uncommon phenomenon (see, e.g., Bąk-Stęslicka et al.

The morphology and spatial evolution of the flare ribbons during the early rise phase have important implications for the initiation of the eruption and reconnection. It is noteworthy that the ribbons formed (i.e., brightening in the chromosphere started) following a fast rise of the flare (Figures 7 and 9). In several recent papers, flux ropes have been identified in images taken in hot EUV channels, namely, 94 and 131 Å (Cheng et al.

As typically observed, we note flux ropes as a bundle of hot coronal loops in the EUV, displaying intense yet diffuse emission. The radio dynamic spectra show an intense patch of type IV emission in the frequency range \(1800-600\) MHz during the activation and eruption of the flare (see type IV continua between \(~6:55-07:01\) UT in Figure 13). It is likely that this early type IV continuum represents intense emission from the non-thermal electrons trapped in the coronal magnetic structure associated with the sigmoid as the reconnection proceeds with the expansion of the flux rope. In conjunction with the early type IV, we observe a number of type III radio bursts during \(06:55-07:01\) UT, which originate at \(~500\) MHz and extend up to \(~50\) MHz. The temporal consistency between the type III and type IV along with combined EUV and HXR images provides a clearer view of the multiple processes occurring simultaneously during the early
rise phase. From these multi-wavelength measurements, we infer that, with the rise of the flux rope, large-scale magnetic reconnection sets in, causing the expansion of loop systems and particle acceleration. The type III bursts then imply the ejection of beams of electrons along the open field lines at relativistic speeds from the reconnection region formed below the erupting flux ropes. The association of type III radio bursts with the early stages of the eruption (i.e., activation of the flux rope) has been observed in earlier studies (see e.g., Joshi et al. 2007). Thus, we find that the eruptive expansion of the flux rope provides the earliest signature of the CME in the source region.

The flare ribbons during the early rise phase exhibit a J-shaped morphology (Figure 9). We particularly emphasize that the eastern ribbon is larger and the hooked part of the “J”-structure appears to be highly curved. It is interesting to note that this region is spatially associated with the expansion of the flux rope from the middle and eastern portions of the sigmoid (see Figures 7 and 9). Recently, Cheng & Ding (2016) investigated the evolution of footprints of erupted magnetic flux ropes from sigmoidal active regions in four events. Their study reveals a common pattern in which the early chromospheric brightenings are located at the two footpoints, as well as in the regions below the two elbows of the magnetic flux ropes, which subsequently evolved into double J-shaped ribbons with the two hooks at opposite ends corresponding to the extended footprints. Further, Zhao et al. (2016) studied the magnetic topology of a sigmoid active region before a major eruption and compared it with the morphology of the subsequently developed flare ribbons. Their study reveals that the morphology of flare ribbons showing hooked or J-shaped structures during the early stages matches with the footprints of the quasi-separatrix layer (QSL; Démoulin et al. 1996; Pariat & Démoulin 2012). Notably, the association of J-shaped ribbons with the footprints of QSLs is consistent with the extended standard model of solar flares in 3D (Aulanier et al. 2012; Janvier et al. 2013). Thus, we believe that the shape and location of the flare ribbons in the chromosphere during the early phases of the eruption have important implications for the geometry of the erupting flux rope and the coronal reconnection sites.

Another important aspect of the flare ribbons during the early rise phase is their converging motions, which essentially mean that they apparently move parallel to the PIL in opposite directions (Figure 9). The converging motions of flare ribbons are further supported by the HXR observations that show a decrease in the distance between conjugate footpoints (Figure 10). The converging motion of flare ribbons is confirmed by some recent observations (Ji et al. 2006, 2007; Liu et al. 2008; Joshi et al. 2009) and, thus, it has been identified as an important phenomenon occurring during the rise phase of flares. In particular, Liu et al. (2008) noted that during SOL2002-04-30, the two conjugate HXR footpoints first move toward and then away from each other, mainly parallel and perpendicular to the magnetic inversion line, respectively. Furthermore, the transition between these two phases of footpoint motions coincides with the reversal in direction of the motion of the looptop source. The explanation of ribbon motions of this kind is still beyond the scope of the standard flare model.

After a prolonged rise phase, the flare exhibited the features of a “standard” large eruptive flare as described by the standard flare model. Here the main observational characteristic of the standard flare is recognized in the form of an increase in the separation of parallel flare ribbons while they move perpendicular to the PIL (Figure 11). Following the eruption of the flux rope, we observed the development of an arcade of coronal loops over the source region that was previously occupied by the coronal sigmoid. This phenomenon, called sigmoid-to-arcade transformation, is well established and theoretically studied in relation to the eruptive dynamics of CMEs (Gibson et al. 2002, 2004). In the radio spectrum, the violent eruption of the flux ropes is followed by the occurrence of a broad, intense type II radio burst, implying the propagation of a shock wave associated with the passage of the CME (see, e.g., Cho et al. 2005). We, therefore, conclude that the standard flare model is well applicable to the late phase of this flare. We believe that, during this phase, the main driver of the energy release process is the large-scale magnetic reconnection driven by the erupting FR.

5. CONCLUSIONS

Sigmoid-to-arcade development is considered to be an important aspect of solar eruptive phenomena. Although the association of sigmoids with eruptions is well recognized, our knowledge about the formation of these structures and their subsequent activation is still limited. In this paper, we provide a comprehensive multi-wavelength investigation of EUV, UV, Hα, X-ray, radio, and magnetic measurements to probe the evolution of a transient coronal sigmoid in active region NOAA 11719, which activates and erupts, leading to a fast halo CME. In the following, we summarize the important results of this study:

1. The observations of the active region in the hot EUV channel of AIA (94 Å) reveal the formation of a large S-shaped FR through a sequence of multiple, localized brightenings involving two large pre-existing coronal loop systems. Considering the fact that the bright emission in 94 Å images corresponds to hot plasma ($T \sim 6$ MK), we attribute the multiple localized brightenings during the loop interactions to repetitive magnetic reconnections. The repetitive reconnection events are temporally and spatially associated with significant variations in the photospheric magnetic flux during the extended pre-eruption period of $\sim7$ hr within the core region that is associated with the formation of the sigmoid.

2. During the formation of the large sigmoid structure in the corona, we observe fast morphological evolution of a filament channel in the underlying layers of the chromosphere and the transition region, observed in AIA 304 Å images. This region also exhibits localized, transient brightenings in conjunction with the episodic energy release in overlying coronal structures. Thus, we propose that the repetitive magnetic reconnections not only play a key role in the formation of the large sigmoidal FR in the corona but also contribute toward sustaining its temperature higher than that of the ambient coronal structures.

3. The early ascent of the FR is associated with the flux cancellation during $\sim1.5$ hr before the eruptive M6.5 flare. Importantly, the central, core region of the sigmoid encompasses the region of flux cancellation. The eruption initiated in the form of expansion of an FR from the core and adjoining elbow regions of the sigmoid. From these observations, we infer that the localized reconnections, likely driven by the $tether$-cutting mechanism occurring in the highly sheared core fields, initiated the early ascent of the FR.
4. The sigmoid eruption leads to a large M6.5 two-ribbon flare. The flare is characterized by a prolonged rise phase of ~21 minutes in SXR. The observation of the early rise phase of the flare prominently exhibits deviations from the standard flare model in terms of converging motions of E(UV) and Hα flare ribbons along with the decrease in the separation of HXR footpoints. More importantly, the flare ribbons during this phase present a J-shaped morphology. We find that the hooked part of the J-shaped eastern flare ribbon is spatially and temporally correlated with the eruption of the overlying FR, providing evidence for a close association between the early morphology of the flare ribbon and the configuration of the erupting FR.

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