Multiwavelength Observations of a Slow Raise, Multi-Step X1.6 Flare and the Associated Eruption

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ABSTRACT

Using multi-wavelength observations we studied a slow rise, multi-step X1.6 flare that began on November 7, 2014 as a localized eruption of core fields inside a δ -sunspot and later engulfed the entire active region. This flare event was associated with formation of two systems of post eruption arcades and several J-shaped flare ribbons showing extremely fine details, irreversible changes in the photospheric magnetic fields, and it was accompanied by a fast and wide coronal mass ejection. Data from the Solar Dynamics Observatory, IRIS spacecraft along with the ground based data from the New Solar Telescope (NST) present evidence that i) the flare and the eruption were directly triggered by a flux emergence that occurred inside a δ -sunspot at the boundary between two umbrae; ii) this event represented an example of the formation of an unstable flux rope observed only in hot AIA channels (131 and 94 Å) and LASCO C2 coronagraph images; iii) the global post eruption arcade spanned the entire AR and was due to global scale reconnection occurring at heights of about one solar radii, indicating on the global spatial and temporal scale of the eruption.

1. Introduction

The overwhelming majority of intense geomagnetic storms that pose danger to the near Earth environment are driven by large scale and coherent magnetic structures called magnetic clouds (Burlaga et al. 1981), which are embedded into coronal mass ejections (CMEs, e.g., Wilson & Hildner 1986; Zhang et al. 2007) that are expelled from the Sun. Magnetic clouds represent an expanding interplanetary-scale system of magnetic loops with electric currents flowing along the field lines so that they coil around the loop's main axis (also called a flux rope, Burlaga et al. 1981; Hu et al. 2014).

Although the existing CME models similarly assume that the flux rope (FR) is contained within the ejecta, they, however, differ in the part that treats the formation of the FR. While some models (Chen & Shibata 2000; Fan & Gibson 2004; Török & Kliem 2005; Kliem & Török 2006) require a FR to be present prior to the eruption, others start from a sheared magnetic arcade (SMA) and create an unstable FR via series of reconnections, which are considered to be a part of the eruption process (Antiochos et al. 1999; Moore et al. 2001; Karpen et al. 2012). Meanwhile, several authors (Aulanier et al. 2002, 2010a; Savcheva et al. 2012) discussed transitional cases, when, on one hand, detailed topological analysis reveals weakly twisted FRs, while the field line plots show only the presence of a SMA (Aulanier 2015). These authors argue that although a real flare most probably does not follow any particular eruption model, it is still crucial for flare forecasting to develop clear-cut discriminators between the FR and SMA scenarios.

The issue about the structure of the pre-eruptive configuration reaches beyond the mere question as to which theoretical model is correct. It involves such fundamental issues of solar activity as the origin and evolution of active regions, source of the energy that drives solar activity and space weather as well as solar flare forecast.

The non-potential sheared fields and FRs may be created in two different ways. The flux cancellation approach (e.g., van Ballegooijen & Martens 1989; Aulanier et al. 2010b) employs an idea that a FR can be gradually formed via reconnection due to continuous shearing and converging of the footpoints of coronal loops. In this case the flare energy is drawn from the motions of photospheric plasma, which distort the initial magnetic configuration thus generating strong current systems that accumulate the free energy. On the other end of the spectrum are models that assume that a helical FR is emerging into the solar atmosphere from the convective zone, thus directly transporting energy from the Sun interior into the exterior. MHD simulations (Fan 2001; Archontis 2008) indicate that a FR ceases to emerge when its axis crosses the photosphere thus producing sheared arcades. The most recent analysis by Török et al. (2014) concluded that active regions are born with substantial current currying loops (see also Abramenko & Yurchyshyn 2010), which confirms the above inference.

Equally important is the unresolved issue of triggering of solar eruptions. A variety of physical mechanisms have been discussed including flux emergence, the magnetic break-out due to shearing flows, MHD instabilities (kink, tourus), and Moreton/EIT waves generated by another eruption or a flare (e.g., Antiochos et al. 1999; Archontis & Török 2008; Lynch et al. 2008; Archontis et al. 2009; Aulanier et al. 2010a; Tziotziou et al. 2013).

The observational challenge in discriminating between various eruption scenarios lies in the fact that large, energetic, and geo-effective events erupt very rapidly in matter of minutes covering a large fraction of an active region with bright flare ribbons, coronal loops and several sources of hard X-ray emission (e.g., Patsourakos et al. 2010; Cheng et al. 2013), which hinders our ability to disentangle the interactions between various magnetic structures. Another problem is that the presence of a FR can only be inferred indirectly, based on a set of signatures such as brightening of "J" or sigmoid-shaped field lines, sequence of flare brightening or the observed pre-flare pattern of field lines.

In this study we consider a slow rise, multi-step eruption that began as a localized flux emergence inside a δ -sunspot and later engulfed the entire active region. We present evidence that i) this event represents an example of an formation of an unstable flux rope immediately prior to the eruption and ii) the flare was directly triggered by a flux emergence that occurred at the site of the flare onset.

2. Data

The X1.6 flare was observed by the New Solar Telescope (NST, Goode et al. 2010) in its entirety as it developed in NOAA AR 12205 located at N15E35 (Figure 1). The NST observations were performed in the photospheric titanium oxide (TiO) band and at the H α spectral line using the Visible Imaging Spectrometer (VIS, Cao et al. 2010). All images were acquired with the aid of an adaptive optics (AO) system, which incorporates a 357 actuator deformable mirror, a Shack-Hartmann wavefront sensor with 308 sub-apertures, and an digital signal



Fig. 1.— SDO/HMI Bz magnetogram plotted over the HMI intensity map (left) and a SDO/AIA 1600 Å image taken after the peak of the X1.6 class flare. In both images the positive (blue) and negative (red) contours are drawn at $\pm 200, \pm 500, \pm 800, \text{ and } \pm 1100 \text{ G}$ levels. The red circle represent RHESSI 12-25 keV emission drawn at $\approx 50\%$ level of the peak intensity. The yellow box outlines the field of view of the NST H-alpha images shown in Figs. 7 and 8. The green box indicates the field of view shown in Figs. 3 and 4. The images were not corrected for the projection effect.

processor system (Zhang et al. 2014). All collected data were speckle reconstructed with the Kiepenheuer-Institut für Sonnenphysik's software package (KISIP, Wöger & von der Lühe 2007) to achieve the diffraction limit of the telescope over a large field of view (FOV).

The photospheric data were acquired every 30 s using a 1 nm bandpass TiO filter centered at 705.7 nm with the pixel scale of 0".0375. This absorption line (the head of the TiO γ -system) is only formed at low temperatures below 4000 K, i.e., inside the sunspots (see Fig. 10 Berdyugina et al. 2003). The VIS combines a 0.5 nm interference filter with a Fabry-Pérot etalon to produce a bandpass of 0.007 nm over a round 70" wide FOV. The imaging of the chromosphere were performed at five position along the H α spectral line with a 0.04 nm step along the spectrum and the pixel size of 0".029. The difference in the acquisition time at two sequential line positions (e.g, +0.04 nm and -0.04 nm) was about 2 s. The five point line scan was recorded every 30 s along the following sequence: -0.08, +0.08, -0.04, +0.04, and 0.0 nm. At each line position we obtained a speckled image with the exposure times ranging from 7 ms (at -0.08 nm) to 25 ms (at the line center).

The Atmospheric Image Assembly (AIA, Lemen et al. 2012) onboard the *Solar Dynamics Observatory* (SDO, Pesnell et al. 2012) acquires full disk EUV images of the Sun (FOV ~1.3 R_{\odot}) with a spatial resolution of 1".5 (0".6 per pixel) and a cadence of 12 s. In this study, we used 171 Å (Fe IX, $T \approx 0.7$ MK), 94 Å (Fe XVIII, $T \approx 6.3$ MK), 131 Å (Fe VIII, Fe XXI, Fe XXIII, i.e., 0.4, 10, 16 MK), 304 Å (He II, T ≈ 0.05 MK) and 335 Å (Fe XVI, $T \approx 2.5$ MK) images. To analyze magnetic environment at the flare site we used Heliospheric and Magnetic Imager (HMI, Scherrer et al. 2012; Schou et al. 2012) $hmi.B_720s$ series data, which are HMI full-disk VFISV ME inverted and disambiguated vector field observations (Hoeksema et al. 2014; Hayashi et al. 2015).

We also utilized the RHESSI data (*Reuven Ramaty High Energy Solar Spectroscopic Imager*, Lin et al. 2002) to investigate the hard X-ray sources related to the particle acceleration sites. Unfortunately, RHESSI missed the pre-flare phase and covered only the peak and decay phases. We used the PIXON algorithm technique (Metcalf et al. 1996) for image reconstruction with an integration time of 1 minute (17:29-17:30 UT).



Fig. 2.— Time variations of normalized positive (blue) and negative (red) magnetic flux measured within the dotted box in Fig. 3, $H\alpha$ -0.8 Å (green) and AIA 1600 Å (bronze) emission as well as the GOES X-ray flux (thick black) and its time derivative (thin black). The gray vertical bar denotes time interval when magnetic flux measurements were affected by the flare emission. The vertical dotted line at 16:54 UT marks the beginning of the sudden rise of the X-ray and the positive magnetic flux. Numbers I through IV mark different stages of the flare, ELS1 and ELS2 indicate moments of eruption of eruptive loops systems (ELS) 1 and 2, while AIA FR indicates the moment when AIA flux rope (FR) was first detected.

3. Results

3.1. Evolution of the photospheric fields

The GOES X-ray time profile (Figure 2) shows that the X1.6 flare was not a typical event characterized by a sudden and rapid rise of X-ray emission followed by a gradual decrease. Instead, the rise phase, which lasted for nearly 30 min, consisted of at least four well defined instances of rapid, step-like soft X-ray flux increase. The time derivative (thin black line) of the soft X-ray profile, which is a proxy for the flare hard X-ray emission (Neupert 1968), shows four peaks and one of them is co-temporal with the period (marked by the gray bar) when the HMI measurements (blue and red curves) were contaminated by the flare emission. We also plot time profile of the total AIA 1600Å intensity calculated over the entire NST FOV to shows the existence of similar separate emission peaks, although some of them are slightly shifted in time relative to the peaks of the soft X-ray derivative.

The green line in Figure 2 is the total intensity of H α -0.8 Å emission calculated over the area where this flare initiated (green box in Figure 1). Until approximately 17:20 UT both the H α -0.8 Å and GOES soft X-ray profiles were well correlated, while the X-ray peak at 17:25 UT does not correspond to any peaks in the chromospheric emission. This is because this strongest energy release occurred far away from the flare triggering location, which was between the sunspots P1 and N1 (see Figure 1). We also would like to point out that the onset time of these series of flares (16:54 UT, the vertical dotted line) coincides very well with the sudden increase of the positive flux (blue curve) and a more gradual increase of the negative flux (red) calculated over the flare initiation site (dotted box in Figure 3).



Fig. 3.— NST/TiO photospheric images over-plotted with contours of HMI vertical magnetic fields. Positive (blue) and negative (red) contours are drawn at ± 200 , ± 500 , ± 800 , and ± 1100 G levels. The dotted box in panel a encloses the area used to monitor magnetic flux variations. Letters N and P mark positive and negative polarity pores discussed in the text. The HMI data were rotated counter-clockwise by 45° to match the orientation of the TiO and H α images in Figs. 7 and 8. The upper panels show evolution of a δ -sunspot as well as penumbral filaments separating them. The lower panels partially overlap with the top ones (N2, P2, and P3) and show appearance of an "orphan" penumbra in the photosphere under the filament (black arrows in panels d and f). The red line segment in panel b marks the position of the slit used to analyze the dynamics of the magnetic fields presented in Fig. 5.

In Figure 1 we show an HMI intensitygram and a SDO/AIA 1600 Å image taken near the flare onset and near the peak of the X-ray flare emission (Figure 2, black line). The over-plotted red circle that outlines the RHESSI 12-25 keV flare peak emission, indicates that the loop top hard X-ray source was associated with a set of sunspots and pores, which were not co-spatial with the flare initiation site. As evident from the AIA 1600 Å image, at the peak of the X-ray flare the ribbons were already well separated. The AIA 171 Å data further showed (see discussion further in the text) that by this time, a post eruption arcade (PEA) has already cooled down to chromospheric temperatures to be well visible in H α images.

In Figure 3 we show series of photospheric TiO images over-plotted with HMI contours that reflect evolution of sunspots and pores during the flare. The H α flare began as two compact and separated bright kernels on both sides of the narrow filamented interface between two umbrae P1 and N1 of a δ -sunspot (see 16:55:39 panel in



Fig. 4.— Top: HMI Bz magnetograms taken at the flare onset (left, 17:00 UT) and two hours after the flare (middle, 18:48 UT) scaled between -1200 G (black) and 1200G (white). The right panel shows their difference with the dark purple (red) color indicating an increase of negative (positive fields). The two thin dotted lines are plotted to ease comparison between the panels. The red line segment indicates the cut along which the field evolution was plotted in Figure 5. P1, P2, N1, and N2 indicate the same sunspots as in Figure 3. Bottom: HMI magnetic field azimuth maps taken at 17:00 UT and 18:48 UT (left and middle) scaled between 0 deg (dark blue) and 360 deg (dark red). The right panels shows their difference with purple colored area indicating azimuthal changes less then 15 deg and red colors representing the changes exceeding 90 deg.

Figure 7). Their location in the TiO images is indicated with the white arrows in panel (a). Very soon another two $H\alpha$ bright patches developed near the lower edge of the N2 pore (its location in the TiO image is indicated by the black arrow, Figure 3, a). By the end of the flare, the N2 pore became notably weaker. As we mentioned above, the total positive magnetic flux calculated within the boxed area (dotted line box, panel a) showed a sudden and well defined increase at the moment of the flare onset. The corresponding TiO movie (S1.mp4) shows that between the P1 and N1 umbrae the highly sheared penumbral-like filaments were first destroyed and then a new filament system formed that directly connected the two umbrae (panel c). One of their footpoints was clearly moving into the N1 suggesting that the filamented structure was associated with an emerging fields rather then reflecting the shrinkage and submergence of magnetic loops.

During the flare, P1 umbra has noticeably shrank: comparing panels (a) and (c) one may notice that the upper light-gray edge of P1 disappeared, while the umbra became more compact and the area of the darkest part has increased, suggesting that the umbral fields became more vertical. The VIS H α data (Figures 7 and 8)



Fig. 5.— Variations (time-distance arrow plot) of magnetic field inclination (left) and azimuth (right) along the red line segment in Figure 4. The x-axis is parallel the solar equator and points to the right, the y-axis is parallel to the rotation axis and the z-axis is in the radial direction. The vertical scales show the length of the slit in arcsec. The time runs from left to right. In the left B_t - B_z diagram, those arrows pointing to the right of the page represent vertical positive fields. Those arrows pointing to the top of the page (center of the plot) represent horizontal fields. In the right B_y - B_x diagram, the arrows represent the magnetic field azimuth. The alength of an arrow is proportional to the intensity of the B_t component. The longest B_t - B_z arrow represents 1700 G fields, while the longest B_y - B_x arrows equals to 2500 G.

reveal that P1 umbra was covered by one of the flare ribbons and some long semi-circular PEA loops were seen rooted there, which further confirms the idea that eruptions may lead to rapid and irreversible changes in the photospheric fields (e.g., Spirock et al. 2002; Yurchyshyn et al. 2004).

In Figure 4 we show HMI vertical (B_z , top) and horizontal (azimuth, bottom) fields as measured at 17:00 UT (flare start, left panels) and at 18:48 UT (middle panels) i.e., well after the flare. The corresponding difference images are shown in the right panels. As expected, the most prominent field change feature is located between P1 and N1 (the purple patch in the upper right panel indicates increased negative fields). At the same time, nearly all positive magnetic elements in this FOV became enhanced as evident from the yellow-red difference structures. The corresponding azimuth images show similar changes, although majority of them are not co-spatial with the B_z variations.

In Figure 5 we show details of the magnetic field variations by plotting the time evolution of B_z and B_t vectors along a line segment running along the P1-N1 boundary (i.e., the y-axis in a time-distance plot). The left set of arrow plots shows that the inclination at the location of the drastic field changes (dotted horizontal line) turned from approximately 50 deg at 17:00 UT (arrows pointing to the upper right corner of the figure) to nearly 120 deg at 18:48 UT, indicating rapid change of magnetic polarity there. The right panel shows the azimuth variations, which we will analyze in combination with the photospheric TiO images to uncover additional details



Fig. 6.— Pre-flare IRIS 1330 Å slit-jaw and Hinode SOT Ca II H images showing the general structure of the flare. The green curves highlight i)the pre-existing loops (PL, panel a) thought to be part of the erupted fields, ii) the expanding core fields (CF, panel b) that triggered the chain of events, and iii) bright erupting fragments B1 and B2, which were also visible in the H α line (B2, Figure 7, top panel) and the AIA channels (ELS1, Figures 9 and 11). The large red rectangle represents the FOV showed in Figs. 7 and 8, while the small green box represents the FOV of Fig. 4.

on magnetic field evolution. Between P1 and N1 at 17:00 UT the HMI azimuth was nearly 90 deg (counting CCW from the top of the image, i.e., from the y-axis), suggesting that the P1 and N1 were connected at the height of formation of the 6173Å spectral line (line core forms at heights of 250-300 km, Norton et al. 2006). At the same time, deeper in the photosphere where the TiO band forms (140 km) images show penumbra-like filaments being sheared and parallel to the P1-N1 boundary, i.e., parallel to the y-axis. Considering that these filaments indicate the field orientation, this disagreement between the HMI and TiO data indicates the presence of a strong vertical shear. However, the situation changed after 18:00 UT. Both HMI and TiO data show nearly identical field orientation of about 140 deg (see the right panel of Figure 5) and the upper right panel in Figure 3), suggesting that both horizontal and vertical shear have been relaxed, possibly due to the flux emergence triggered eruption of these core fields.

Another notable photospheric field changes are indicated with an arrow in panels (d) and (f) of Figure 3. An irregular granulation pattern first appeared there at the flare onset and then developed into an extended system of elongated granules and short penumbra-like filaments (called "orphan" penumbra, arrow in panel f). This pattern is known to be associated with low lying horizontal fields and may indicate the presence of either Ω or U-shaped fields (Strous & Zwaan 1999; Cheung et al. 2008; Yurchyshyn et al. 2012; Kuckein et al. 2012; Lim et al. 2013). However, this penumbra like pattern was only associated with positive polarity fields, which according to Figures 7 and 8 appeared to be under a chromospheric filament, FL, that remained undisturbed throughout the flare.

3.2. Development of the flare in the low atmosphere and the corona

We will further discuss the evolution of the flare based on Figures 6 - 11. The onset of the flare between the two umbrae appeared to be triggered by reconnection of highly sheared fields, such as hypothesized loop systems



Fig. 7.— NST/VIS H α -0.8 Å images of the X1.6 flare on Nov 7, 2014 during the early phase. The arrows in the lower panel indicate sites of initial flare brightenings associated with the P1 and N1 umbrae. The blue/yellow contours represent 17:00 UT HMI vertical positive/negative fields plotted at \pm 50, \pm 500, \pm 800, and \pm 1100 G. The field of view is 22"×6" and corresponds to the yellow box in Fig. 1. The images were not corrected for the projection effect.



Fig. 8.— NST/VIS H α -0.8Å images of the X1.6 flare on Nov 7, 2014 during the peak of the flare (17:31 UT) and the formation of the post eruption arcade. The blue/yellow contours represent co-temporal HMI vertical positive/negative fields plotted at $\pm 50, \pm 500, \pm 800, \text{ and } \pm 1100 \text{ G}$. The black and gray patches inside the flare ribbons (bottom panel) are due to saturation of the detector. The field of view is $22'' \times 8''$. The images were not corrected for the projection effect.

LS1 and LS2 (Figure 7, lower panel). Shortly after the flare onset several instruments (SDO/AIA, Hin-

ode/SOT Ca II H, and NST/VIS) detected bright core field loops (CF, Figures 6-11), which emerged from the δ -sunspot. The CF quickly expanded up and seemingly came into contact with the loop system, PL, seen in the pre-flare IRIS 1330 Å image still bright from an earlier flare. The relevant NST H α images and a movie (S2.mp4) showed rapidly evolving loops that appeared to connect the umbra interface and the negative pore N2. At ~16:56 UT the CF system began to break up and two oppositely directed bright branches B1 and B2 appeared near the top of CF (panels c-f) in SDO, IRIS UV and H α lines. At the same time, narrow flare ribbons began to form along the filament, FL.

According to the SDO/AIA images, these branches were part of a much larger eruptive loop system (ELS1, Figure 9, c, d). Soon after the ELS1 appeared, thin flare ribbons began to form along the filament, FL, and the first signatures of the H α PEA appeared about 15 min later (Figure 8). We note that this PEA was almost entirely visible in the red-wing of the H α line and only faint traces of some loops where seen in the blue-wing of the spectral line. This is rather an unusual behavior since only footpoints of a typical PEA appear red-shifted, while the top of the arcade tends to be blue-shifted. This figure also evidences that at the peak of the X-ray flare at 17:30 UT the PEA was already well developed thus confirming that a multi-step eruption was taking place. The 17:50 UT H α +0.4 Å image indicates that the filament, FL, was still present in the AR, while the far wing H α +0.8 Å image highlights complexity of the newly formed PEA as well as shows a part of magnetic structures moving laterally away from the filament and the main magnetic axis of the AR.

The AIA 304 Å and 171 Å images taken at 17:09 UT seem to suggest that the ELS1 was kinked (indicated by arrow) and untwisting in the clockwise direction (right handed twist, see movie S3.mp4). Interestingly, at 17:17:50 UT another tongue shaped structure to the left of ELS1 became disturbed and erupted as well (ELS2, Figure 9, e-f) revealing what seems to be untwisting counter-clockwise motions (left handed twist, see S3.mp4 AIA 304 Å movie). It appears as if the sequential eruptions of ELS1 and ELS2 were linked (*i.e.*, coupled/sympathetic eruption).

Both ELS1 and ELS2 showed untwisting/unwinding motions, which most likely were the result of developing of a kink instability (Török & Kliem 2003; Török et al. 2004; Kliem et al. 2004). Such motions were observed in other erupting events (e.g., Kumar et al. 2012; Kumar & Cho 2014). While the ELS1 appeared kinked and experienced clockwise rotation, the ELS2 was rotating counterclockwise. Chandra et al. (2009) argued that the "J" and reverse "J"-shaped flare ribbons may be signatures of various helicities in active region magnetic fields. In our case, both R1 and R2 ribbons were "J"-shaped (Figure 10) that suggests positive helicity and thus the associated ELS1 should display a right handed twist. Similarly, the data seem to suggest that the counterclockwise rotation of the ELS2, and the associated reverse "J"-shaped ribbon, R3, may indicate the left hand twist, although this inference is not firm. Consequently, the ELS1 and ELS2 should be treated as two erupting and separate structures rather than as two legs of one erupting magnetic loop.

3.3. Formation and Evolution of a Flux Rope

To further study evolution of these erupting magnetic fields, we utilized AIA 131 Å and 94 Å images (Figure 11). We argue that a series of reconnection events led to the formation of an unstable FR. A doughnut-shaped faint structure can be seen in the AIA 94 Å 17:10:49 UT panel with a dark center, which is reminiscent of the cross-section of a FR. This structure was gradually expending and in the following images it is already seen filling the second quadrant of the FOV (e.g., see the 17:14:12 UT panel) and revealing series of semi-circular field lines. Interestingly, the bright remnants of the ESL1 structure seem to be visible below the rising FR and they followed the flux rope during the eruption process.

In Figure 12, we show 1 min running difference AIA 171, 94 and 304 Å images. In the low corona, the cool loops overlying the rapidly expanding FR were compressed and heated to become visible as frontal loops. We should emphasize that the frontal loops are not the PEA, which have not yet formed at this time and will only



Fig. 9.— AIA 171, 304, and 335 Å images during the flare and eruption of ELS1 and ELS2 structures. The x and y-axes in each image are in arcsecs. (Online animation of this figure is available).





Fig. 10.— AIA 1600 Å image with the overplotted box indications the NST FOV. R1, R2, and R3 mark three "J" and inverse "J"-shaped flare ribbons. The ELS1 was related to R1 and R2 ribbons, while the ELS 2 was associated with the R3 ribbon.

appear after the FR takes off. The blue S1, S2, and S3 lines are the slice cuts used to create stack plots of running difference intensity (Figure 13). The GOES soft X-ray flux in 0.5-4 Å channel is over-plotted again in the top panel. The slow rise of the circular flux rope started at 17:08 UT (Figure 13, c) when the soft X-ray emission began to plateau, i.e., presumably at the peak of the associated hard X-ray emission (see the bronze AIA 1600 Å curve in Figure 2). Subsequently, the eruption of ELS1 and ELS2 began at 17:12 and 17:18 UT, which corresponds to two small peaks of the AIA 1600 Å emission.

The first two top bright tracks in panel (c) are the parts of the circular flux rope, whereas the lowest track represents the bright plasma structure ELS1 running behind the rising flux rope (refer to AIA 94 Å channel movie, S2.mp4). The initial projected speed of the rising FR derived from a linear fit was $\sim 120\pm15$ km s⁻¹ and it has later accelerated to $\sim 250\pm15$ km s⁻¹. Panels (a) and (b) represent dynamic tracks for ELS1 and ELS2 as seen in the 304 Å channel. Their projected on the sky plane speeds are $\sim 250\pm30$ km s⁻¹ and $\sim 390\pm10$ km s⁻¹, respectively. By measuring the cross-section of the FR in the AIA 94 Å 17:10:49 UT image (Figure 11) and LASCO C2 image (see text below and panel a in Figure 14) we could estimate the average FR expansion rate, which was found to be about 120 km/s indicating that the FR expanded 10-fold during an approximately 90 min time interval. Therefore, the 120 km/s projected speed determined from the dynamic track most probably reflected the flux rope expansion rather then actual rise of the flux rope axis. After the FR expanded it took off at about 17:12 UT together with the ELS1 that was visible mainly at the lower part of the FR.

Figure 14 shows that the X1.6 flare was followed by a moderately fast coronal mass ejection (CME), which was first detected in the SOHO/LASCO C2 coronagraph at 18:08 UT. According to the CACTus CME Catalog¹ (Bonte et al. 2011) the speed of the CME ranged from 224 km s⁻¹ to 2016 km s⁻¹ depending on the position angle, with the average value of 938 km s⁻¹. The SEEDS ² catalogue (Olmedo et al. 2008) reported an average

¹http://sidc.oma.be/cactus/catalog/LASCO/2_5_0/qkl/2014/11/CME0062/CME.html

²http://helio.gmu.edu/seeds/dailymkmovie.php?cme=20141107



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Fig. 11.— AIA 131 and 94 Å images showing expansion of the flux rope (FR). The x and y-axes in each image are in arcsecs.

value of ${\sim}505~\text{km}~\text{s}^{-1}$ with a negative acceleration of ${\sim}122~\text{m}~\text{s}^{-2}.$

A well defined circular structure was seen embedded into the CME (Figure 14, a). According to Vourlidas (2014) it may be interpreted as a coronal FR, most likely the same we observed in the hot AIA channels. The original LASCO C2 images show presence of dense material in the lower left section of the coronal FR, which are cold and dense plasma trapped during the reconnection and formation of the FR. These are most likely parts of the ELS1 structure. It is also worth noting that the bright CME envelope (driven shock), is much wider than the embedded FR, which may be either due to projection effect or reflect the fact that this was a complex ejecta, most probably hosting two flux ropes. Finally, the 20:36:05 UT C2 image shows X-shaped magnetic field lines (arrows) below the coronal FR, which has left the C2 field of view at that moment. This allows us to conclude that the CME eruption was probably driving a global scale magnetic reconnection, which may have added additional azimuthal flux to the erupting and yet still forming flux rope. Full disk BBSO H α images confirm this inference by revealing the existence of a second PEA that spanned the entire active region (Figure 15). The arcade first appeared in H α spectral line at about 19:00 UT, well after the X1.6 flare and lasted until approximately 20:35 UT. SDO AIA 171 Å data (not presented in the paper) showed that between 18:12 UT and 18:28 UT a system of large scale loops in the west part of the AR (a location co-spatial with ELS2, Figure 11, c) suddenly brightened and began to gradually grow at a low rate. This AIA loop system seemed to be only associated with a part of the AR, however, it was visible until about 24:00 UT. Taken together, these observations may indicate the ongoing reconnection high in the corona as predicted by the CSHKP model (see, for example, Shibata et al. 1995) and suggest the global scale of that particular eruption.



Fig. 12.— AIA 171 and 94 Å difference images showing frontal loops (left panel) enclosing the expanding flux rope (middle). The right panel shows AIA 304 Å difference image with the erupting ELS2 rotating in the counterclockwise direction. The S1, S2, and S3 are the slits used to generate the stack plots shown in Figure 13. The x and y-axes in each image are in arcsecs.

4. Summary and Conclusions

We conclude the following. i) Flux emergence inside a δ -sunspot at the boundary between two umbrae was observed and it triggered eruption of magnetic fields. ii) Series of reconnections involving different magnetic flux systems led to formation of an unstable flux rope in the low corona, which was observed in the hot AIA channels as a system of expanding and rising helical field lines. iii) This non-typical flare produced two PEA systems. The first one appeared at 17:15 UT, was occupying only a part of the AR and spanned an undisturbed filament. The second PEA appeared after 18:30 UT and spanned the entire AR, indicating on the global spatial and temporal scale of the eruption.

Emergence of a new magnetic flux system inside a δ -type sunspot, evidenced by co-temporal and co-spatial increase of the HMI magnetic fields, triggered an eruptive X1.6 flare associated with a CME. This was a flare with several distinct stages of energy release, delayed appearance of flare ribbons, and a slow rise of the X-ray flux. The data further suggest that before the main eruption several localized reconnection events occurred in different parts of the AR, which lead to formation of a flux rope.

The photospheric NST/TiO images showed an enhanced dynamics at the interface between the positive and negative umbrae of the δ -sunspots co-spatial with the flare initiation site. The orientation of the penumbrallike filaments separating the umbrae had changed from being highly sheared and parallel to the umbrae edge, to nearly disappearing, to being nearly orthogonal and connecting them. The corresponding HMI data showed similar variations in the vector field (see Spirock et al. 2002; Yurchyshyn et al. 2004; Sudol & Harvey 2005; Wang 2006, for other events). The data also clearly showed that the flare related increase of the magnetic field intensity occurred due to both reconfiguring of coronal magnetic fields (i.e., formation of a PEA rooted in the umbra) and emergence of a new flux. We note that there were other locations where photospheric field changed, such as the appearance of a "orphan" penumbra (Strous & Zwaan 1999; Cheung et al. 2008; Yurchyshyn et al. 2012; Kuckein et al. 2012; Lim et al. 2013) developed under a stable chromospheric fielament, although it is not obvious that these changes either led to or were caused by the flare.

The AIA images taken in the hot channels (94 Å and 131 Å) indicated that an unstable flux rope was formed and erupted during the event. This slow rise event consisted of at least four major and distinct reconnection events: i) 16:54 UT — flare trigger by eruption of core fields, CFs, from the δ -sunspot and activation of the first loop system CLS1; ii) 17:03 — first coronal signatures of an expanding FR and ELS1 followed by the appearance of flare ribbons; iii) 17:15 UT — eruption of the flux rope and the second loop system, CLS2; and iv) 17:20 UT the onset of a long lasting RHESSI event, accompanied by an post-eruption arcade covering the entire active region.

It is also worth emphasizing that RHESSI did not collect data during the first three events and we can not rule out formation of hard X-ray sources associated with reconnection in the lower atmosphere. During the fourth/last energy release events, the precipitation of non-thermal electrons (see AIA 1600 Å movie) took place mostly toward the western side of the core region and we see the emission from the loop-top source most likely by trapped electrons.

The flux rope observed here is similar to the 3 November 2010 flux rope that was also only observed in the hot AIA channels (131 Å and 94 Å Cheng et al. 2011; Hannah & Kontar 2013; Kumar & Innes 2013; Mulay et al. 2014). It showed plasma inflows behind it (Savage et al. 2012), and was interpreted as an magnetic breakout reconnection event (Kumar & Innes 2013). However, because the 3 November 2010 flare was a limb event, it was impossible to analyze the magnetic field evolution in the photosphere. Our event seems to support the torus instability scenario, showing that a FR can first be formed by a series of reconnection events and then expand without rising its axis significantly. The FR expansion also stresses and expands the surrounding fields increasing the decay index until it exceeds the threshold for the onset of torus instability (Kliem & Török 2006; Zuccarello et al. 2014). Nevertheless both events are presenting evidence that flux emergence and eruption of the core fields may trigger multiple reconnections to form a helical FR.

LASCO C2 images confirm that a FR structure has erupted from the AR by showing a circular and ascending feature enclosed within the ejecta, which are generally interpreted as flux rope structures (Vourlidas 2014). The bent loops in LASCO C2 images (also see Yurchyshyn 2002), the secondary PEA observed in the H α line, and the large, long living AIA 171 Å arches indicate a reconnection process occurring high in the corona, involving global fields and lasting for hours after the flare. Taking the measured speed of the ejecta at a constant 500 km s⁻¹ gives us that the reconnection lasted at least until the ejecta has reached the 15 solar radii mark. This secondary PEA can be interpreted as a giant post-flare arch (Poletto & Kopp 1988), which are created during a reconnection process that is distinct from the flare reconnection (also see Svestka et al. 1982; Yurchisin 1994; West & Seaton 2015). The reconnection occurs high in the corona far above the flare site and it involves magnetic loop systems that originally span the entire AR and are distinct from those involved in the flare.

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Fig. 13.— Stack plots produced along the slits S1, S2, and S3 using series of AIA 304 and 94 Å running difference images. The blue curve in the top panel is the GOES 0.5-4 Å soft X-ray flux profile. The first vertical dashed line marks the appearance of the flux rope in AIA hot channels 94 and 131 Å whereas the second line marks the eruption of ELS2.



Fig. 14.— The coronal mass ejection (CME) on Nov 7, 2014 as seen in SOHO/LASCO C2 difference images. This was a wide ejecta with a much smaller circular flux rope (FR) structure embedded in part of it. Long after the flux rope left the C2 field of view, bent parts of loops presumably overlying the FR were still visible in the C2 images (right panel, arrows).



Fig. 15.— Partial fields of view of full disk BBSO $H\alpha$ images showing evidence of a global post-eruption arcade (PEA) spanning the entire active region. The first faint signatures of the global PEA appeared at shorty before 19:09 UT and the PEA disappeared from the $H\alpha$ line at shortly after 20:30 UT.

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