Are Complex Magnetic Field Structures Responsible for the Confined X-class Flares in Super Active Region 12192?

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Abstract

From 2014 October 19 to 27, six X-class flares occurred in super active region (AR) 12192. They were all confined flares and were not followed by coronal mass ejections. To examine the structures of the four flares close to the solar disk center from October 22 to 26, we firstly employ composite triple-time images in each flare process to display the stratified structure of these flare loops. The loop structures of each flare in both the lower (171 Å) and higher (131 Å) temperature channels are complex, e.g., the flare loops rooting at flare ribbons are sheared or twisted (enwound) together, and the complex structures were not destroyed during the flares. For the first flare, although the flare loop system appears as a spindle shape, we can estimate its structures from observations, with lengths ranging from 130 to 300 Mm, heights from 65 to 150 Mm, widths at the middle part of the spindle from 40 to 100 Mm, and shear angles from 16° to 90°. Moreover, the flare ribbons display irregular movements, such as the left ribbon fragments of the flare on October 22 sweeping a small region repeatedly, and both ribbons of the flare on October 26 moved along the same direction instead of separating from each other. These irregular movements also imply that the corresponding flare loops are complex, e.g., several sets of flare loops are twisted together. Although previous studies have suggested that the background magnetic fields prevent confined flares from erupting, based on these observations, we suggest that complex flare loop structures may be responsible for these confined flares.

Key words: Sun: activity – Sun: atmosphere – Sun: corona

Supporting material: animations

1. Introduction

The flares associated with coronal mass ejections (CMEs) are termed “eruptive flares” and the eruptive flares usually last for a long period of time, from tens of minutes to hours (e.g., Zhang et al. 2007). Some flares are not accompanied by CMEs in the wake of the eruption (Ji et al. 2003); these flares are called confined flares (e.g., Wang & Zhang 2007). The occurrence rate of eruptive flares is dependent on the flare intensity and duration (Kahler et al. 1989; Andrews 2003). The fraction of flares that is associated with CMEs increases rapidly from small flares to large X-class flares, reaching close to 100% for the largest ones. For example, Yashiro et al. (2005) found that the fraction of flares associated with CMEs increases from 20% for C3–C9 flares to 100% for flares above X3. Wang & Zhang (2007) reported that whether a flare is eruptive or confined is determined by the distance between the flares and the active regions (ARs), such as 22–37 Mm for eruptive flares and 6–17 Mm for confined flares. On the other hand, the overlying magnetic arcades provide strong confinement, and are believed to play an important role in the failed eruptions (e.g., Török & Kliem 2005; Guo et al. 2010; Cheng et al. 2011; Chen et al. 2013).

To explain the physical mechanism of eruptive events, many theories and models have been proposed in which the overlying magnetic loops must be opened so that plasma and magnetic flux can escape (Forbes et al. 2006). For the eruptive flares, a rising flux rope stretches the overlying magnetic lines, then a magnetic reconnection between the stretching lines takes place (Sturrock 1966; Masuda et al. 1994; Shibata et al. 1995; Tsuneta 1996). The confined flares are mainly affected by the surrounding coronal magnetic fields. Török & Kliem (2005) and Fan & Gibson (2007) revealed that while the overlying arcade field decreases slowly with height, a confined event is permitted. Furthermore, the calculations from the potential field surface-source model showed that stronger overlying magnetic arcades will prevent energy release, thus resulting in confined flares (Wang & Zhang 2007; Guo et al. 2010; Chen et al. 2015).

A large number of simulations questioning whether a configuration fully or partly erupts have been investigated. Examining the magnetohydrodynamic (MHD) stability, analyzing nonlinear force-free field models, and employing the techniques of flux rope insertion (van Ballegooijen 2004; van Ballegooijen et al. 2007) and magnetofrictional relaxation (Yang et al. 1986), Kliem et al. (2013) confirmed that the MHD treatment of the eruptive configuration can make some observed features reappear. Considering the condition that a toroidal flux rope embeds in a bipolar or quadrupolar external field, catastrophe and torus instability occur at an X-line under the flux rope where magnetic reconnection takes place (Kliem et al. 2014a). Through studying force-free equilibria containing two vertically arranged magnetic flux ropes (Titov & Démoulin 1999; Liu et al. 2012), Kliem et al. (2014b) demonstrated several conditions for the two rope activities, e.g., both the ropes turn unstable, both the ropes erupt upward, and only the upper rope erupts while the lower rope reconnects with the ambient flux.

In this work, we report four confined X-class flares by analyzing the complex flare loops, using observations from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and...
the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). The data from the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014) are also employed to display the special evolutions of these flare ribbons. In Section 2, we describe the observational data. The results are presented in Section 3. Section 4 features the conclusions and a brief discussion.

2. Observations

SDO/AIA observes the Sun in 10 wavelengths with a 0″6 pixel size and a 12 s cadence. These data reveal the solar atmospheric temperatures from ~5000 K to ~20 MK. The SDO/HMI records the full disk line of sight (LOS) magnetic field with a cadence of 45 s and a spatial sampling of 0″5 pixel⁻¹. We use the observations of 131, 171, and 1600 Å to investigate the evolutions of flare loops and ribbons, and the LOS magnetograms are applied to display the photospheric magnetic fields of these loops. The data adopted here were obtained from 2014 October 22 to 26, while AR 12192 was near the solar disk center. We have de-rotated the AIA data to the same time (October 23 15:00 UT). Furthermore, two sets of IRIS 1330 Å data are employed. The first set of IRIS observations was taken from 08:18 UT to 18:07 UT on October 22, with a cadence of 33 s, a pixel scale of 0″16, and a field of view (FOV) of 120″ × 119″. The second was taken from 23:01 UT on October 25 to 11:15 UT on October 26, with the same pixel scale and FOV of the first set, but the cadence is 18 s. The 1330 Å channel contains emission from the strong C ii 1334/1335 Å lines that are formed in the upper chromosphere and transition region. In order to compare the Doppler shifts between the confined flare on October 26 and an eruptive one, we select a set of IRIS data for the eruptive X-class flare on 2014 September 10. These IRIS observations were taken from 11:28 UT to 17:58 UT, with a FOV covering the majority of the AR 12158 (Li & Zhang 2015).

3. Results

3.1. Overview of AR 12192

Because it hosts the largest sunspot group since 1990, AR 12192, observed in 2014 October, has been paid significant attention (e.g., Sun et al. 2015; Thalmann et al. 2015). According to the statistics by Chen et al. (2015), when AR 12192 passed across the visible solar disk from October 18 to 29, it produced 6 X-class and 29 M-class flares. However, there was only one M-flare related to a CME (Li et al. 2015). These X-class flares had a similar origin within the AR and common spatial and timing characters, implying they were homologous flares (e.g., Zhang & Wang 2002; Sui et al. 2004; Yang et al. 2014), and Chen et al. (2015) suggested that tether-cutting reconnection (Moore et al. 2001) could trigger these homologous flares. Thalmann et al. (2015) provided evidence for repeated energy release, indicating that the same magnetic field structures were repeatedly involved in magnetic reconnection. Sun et al. (2015) studied the magnetic conditions of the AR and suggested that the magnetic non-potentiality over the restriction of background field limited the eruptions. Photospheric motions of emerged magnetic fluxes lead to shearing of the associated coronal magnetic field, which then yields a tether-cutting favorable configuration (Chen et al. 2015).

3.2. Complex Flare Loops

One outstanding feature of AR 12192 is its poor CME production rate, despite the many X-class flares observed during its disk passage. Previous studies suggested that the overlying background field of the AR may play an important role in these confined flares. In this work, we focus on the complex flare loops themselves. Four X-class flares (from 2014 October 22 to 26) that occurred close to the solar disk center are studied. Figure 1 displays the loops of the first studied X-class flare (X1 in Figure 1(a)) on 2014 October 22. During the flare process, the flare loops at higher temperatures (e.g., 131 Å, Figures 1(d)–(f); see also the online animated version of Figure 1) were more abundant than those at lower temperatures (171 Å, Figures 1(a) and (b)). These loops displayed complex structures, such as the loops that are sheared relative to each other in Figure 1(e), and are rooted at two flare ribbons that were more evident at 171 Å (Figure 1(a)) and 1600 Å (Figure 1(c)). From the corresponding LOS magnetogram (Figure 1(g)), we note that the left ribbon overlaps the negative polarity fields, and the right ribbon overlaps positive fields.

To better show these flare loops, we employ, for the first time, composite triple-time images of 131 Å observations that can clearly display the complex loops during flare processes. Composite triple-filter images (e.g., Zhang et al. 2015) from SDO/AIA are widely used to display the different temperature structures in the solar atmosphere. The composite triple-time images are derived from the hint of composite triple-filter images, and are produced by imitating the composite triple-filter images. The imitation is based on the observational fact that the flare loops brighten successively from lower to higher atmospheric levels in the flare process. In other words, each set of flare loops seems immobile during the flare process. While we display these successively brightened loops with different colors in one image, a stratified structure of these flare loops appears. For example, in Figure 1(h) the blue loops are lower and shorter, yellow loops are located at the middle layer, and the red loops are higher and longer, and are located at the highest layer. The majority of the flare loops are rooted at a small region on the left, but on the right the loops are rooted at a long extending ribbon, thus appearing as a spindle structure (see Figures 1(c) and (h)). The lengths of flare loops can be reliably measured. Assuming that the loops are semicircular configurations, the corresponding height (equaling half of the length) can also be determined. To describe the properties of these loops, which are the lengths and heights (widths) of particular loops (loop systems) of the first flare, the lengths and heights of the other three flare loops are listed in Table 1. The assumption may not be well justified in complex ARs, as the loops have a more complicated geometry that is far from circular. The heights of the loops in each flare are for reference only. To quantitatively describe the complexity of the flare loops, shear angles in the first two flares are measured by comparing the observed loops with the AR’s prime neutral lines deduced from the magnetograms. The flare loops have a higher non-potentiality, e.g., strong shear (or deviating from potential fields) in 131 Å images. The shear angles of X1 loops distribute from 16° to 90° (see Table 1).

Figure 3 shows the loops of the second studied X-class flare (X2 in Figure 3(a)) on 2014 October 24. Similar to the first flare displayed in Figure 1, this flare also shows complex loop structures. The twisted loops were observed at lower (171 Å, Figures 3(b) and (c)) temperature wavelengths, and the shear...
angles were estimated from 30° to 85° (see Figure 3(h) and Table 1). The last two X-class flares, which occurred on October 25 and 26, are displayed in Figure 4. Also, these flare loops were non-potential, and the shear of the loops was evident (see Figure 4(b) and the window region of Figure 4(f)). As the third and fourth flares were near the solar limb, the widths and the shear angles of their flare loop systems cannot be reliably measured. During all four X-class flare processes, the complex structures had not been destroyed. Also, a signal for the opening and shrinkage of these flare loops was not evident.

3.3. Special Evolution of Flare Ribbons

Previous studies for these flares have realized that the large initial separations of these flare ribbons, together with an almost absent growth in ribbon separation, suggest a confined reconnection site high up in the corona. Two sets of IRIS 1330 Å data with high spatial resolution allow us to investigate in detail the evolutions of the ribbons of the first and the fourth flares. Figure 2 is a time series of the first set of IRIS 1330 Å images (also see the online animated version of Figure 2), which show the evolution of four fragments (marked by “R1,” “R2,” “R3,” and “R4,” respectively) of the flare “X1” ribbons (see Figure 1). “R1,” which belongs to the right ribbon and appears as a hook, propagates leftward. The moving speed of “R1” has been deduced by examining the evolution of the ribbons observed from IRIS images. As the spatial resolution of the IRIS data is much high (0.16 per pixel), and the moving process lasted a long time (13.5 minutes, see Figures 2(a) and (e)), the speed error is small. Considering the position error is 2 pixels while we measure the speeds, the speed error is 0.6 km s⁻¹, so the propagating speed is 19 ± 0.6 km s⁻¹ (Figure 2(e)). The three fragments “R2,” “R3,” and “R4” belong to the left ribbon of the flare. They appear successively, and repeatedly sweep a small region anticlockwise. Another evolution pattern of flare ribbons revealed by the second set of
Spatial Scales and Shear Angles of the Flare Loops (Loop Systems) in X1–X4

| Parameter | X1       | X2      | X3      | X4      |
|-----------|----------|---------|---------|---------|
| Length (Mm) | 130–300  | 173–480 | 214–420 | 150–400 |
| Height (Mm)  | 65–150   | 86–240  | 107–210 | 75–200  |
| Width (Mm)   | 40–100   | ...     | ...     | ...     |
| Shear angles (°) | 16–90   | 30–85   | ...     | ...     |

IRIS 1330 Å data is both of the two ribbons move along the same direction, instead of separating from each other. Figures 5(a) and (b) show the evolution of two ribbons of the fourth flare (X4) in the field of view outlined in Figure 4(f). Both the ribbons move rightward, with a speed of $11 \pm 0.5 \text{ km s}^{-1}$ ($19 \pm 0.5 \text{ km s}^{-1}$) for the left (right) ribbon (see Figure 5(c)).

3.4. Different Doppler Shifts between a Confined Flare and an Eruptive One

As there is no material escaping from the solar atmosphere in a confined flare process, the Doppler shifts between a confined flare and an eruptive one will be different. We compare the confined flare (X4) on 2014 October 26 with the eruptive one on 2014 September 10. Figure 5(d) shows the variation of the GOES soft X-ray flux (blue curve) in the X4 flare duration. The black cross symbols show the Doppler shifts in the position (denoted by a yellow cross symbol in Figure 5(b)), which are located in the middle region of the two flare ribbons. The redshift velocities ($10–30 \text{ km s}^{-1}$) are almost stable during the flare process. Furthermore, Figures 4(e)–(h) have already shown that these flare loops are restricted to a limited region. For the flare with a mass ejection on 2014 September 10, we cannot truly plot the heights of the flare loops above the photosphere where the Doppler velocity has been measured, as the loops at the position rise almost along the LOS. Fortunately, we can track the loops that cross over the position (where the Doppler velocity has been measured), from one footprint to another one, so the relative height of the loop at other positions can be truly measured (see Figures 5(e)–(g)). Near 17:25 UT on 2014 September 10, the projective height of the loops reached 100 Mm, and the rising speed exceeded $200 \text{ km s}^{-1}$. Moreover, the eruptive X-class flare displayed different Doppler shifts, e.g., at the later phase of the flare, the redshift velocities in the middle of the two ribbons increased from $30 \text{ km s}^{-1}$ to about $80–100 \text{ km s}^{-1}$ (Figure 5(h); see Li & Zhang 2015).

4. Conclusions and Discussion

Examining the evolution of the four flares from October 22 to 26, we note that the loop structures of each flare in both lower (171 Å) and higher (131 Å) temperature channels were complex, e.g., the flare loops rooting at flare ribbons were twisted (enwound) together, displaying strong shear among loops and evidently non-potential features of the flare loops. IRIS observations show that the flare ribbons underwent irregular movement, such as the left ribbon of the flare on October 22 repeatedly swept a small region, and both ribbons of the flare on October 26 moved along the same direction,
instead of separating from each other. By comparing the confined flare X4 with the eruptive one on 2014 September 10, we find that the eruptive flare displayed a strong Doppler redshift enhancement and the rising speed of the flare loops reached 200 km s$^{-1}$ at the late phase of the flare, but no redshift enhancement for the confined one, implying that the complex

Figure 3. Panels (a)–(c): 171 Å images showing the loops of the second studied X-class flare (X2 in Figure 3(a)) on 2014 October 24 at lower temperatures. The crossed red and blue curves in Figures 3(b) and (c) represent the twisted flare loops. Panel (d): corresponding LOS magnetogram. Contours, lines, and pluses are the same as in Figure 1(g). Panels (e)–(g): 131 Å images showing the loops at higher temperatures. The black curves in Figures 3(e)–(g) outline the lengths (see Table 1) of the loops at different times. Panels (h): composite triple-time images of 131 Å images consisting of 21:09 UT (blue), 21:17 UT (green), and 21:38 UT (red) images. Curves, lines, arrows, and the angle are the same as in Figure 1(h).

Figure 4. Panels (a)–(c): 131 Å images showing the loops of the third studied X-class flare (X3 in Figure 4(a)) on 2014 October 25 at higher temperatures. The blue, yellow, and red curves outline the lengths of the loops, and are duplicated in Figure 4(d). The two yellow arrows in Figure 4(b) denote the shear loops. Panel (d): composite triple-time images of 131 Å images consisting of 16:50 UT (blue), 17:02 UT (green), and 17:28 UT (red) images. Panels (e)–(g): similar to Figures 4(a)–(c). 131 Å images showing the loops of the fourth studied X-class flare (X4 in Figure 4(e)) on 2014 October 26. Panel (h): similar to Figure 4(d), composite triple-time images of 131 Å images consisting of 10:09 UT (blue), 10:47 UT (green), and 11:09 UT (red) images. The yellow window in Figure 4(f) outlines the FOV displayed in Figures 5(a) and (b).
Based on these observations, we suggest that the complex flare structures tie themselves up, and there is not enough energy to untangle these fastened structures, thus these flares are observed as confined ones.

In previous studies, the dominant idea for interpreting confined flares was that the overlying loops prevent the flares from being eruptive. Indeed, there are some large-scale coronal loops above the confined flares that are observed (Yang et al. 2014). However, the complex flare loops may also play a key role but it is always omitted. In fact, observations reveal that there are many loops involved in a flare, and these loops will erupt if the flare is an eruptive one. Under the condition that these eruptive loops are individual, e.g., potential field loops, the overlying loops should fully cover all these individual flare loops to prevent them from erupting. So we should observe a network (or a dome) that consists of the overlying loops enwrapping the flare loops. On the contrary, only one or two sets of overlying loops (arcades) are detected during confined flare processes (Chen et al. 2013; Yang et al. 2014). This evidence suggests that the flare loops are not individual, but instead they are enwound together, so one or two sets of
overlying loops can prevent them from erupting. Our observations support the notion that the loops of each studied flare are indeed enwound together. Liu et al. (2014) reported a confined flare with a quasi-static cusp-shaped structure that consisted of multiple nested loops, implying that the flare loops are also enwound together.

Further evidence for displaying the complex flare loops is the evolution of the flare ribbons. The flare ribbons are considered as maps of the energy release sites in solar flares. The movement of the ribbons and its relationship to magnetic fields are important for understanding the magnetic reconnection process. The two ribbons in many flares appear to separate from each other during the development process of the flares (e.g., Fletcher & Hudson 2002; Qiu et al. 2002; Asai et al. 2004; Veronig et al. 2006; Miklenic et al. 2007; Temmer et al. 2007; Li & Zhang 2009). In our studied events, the two ribbons of each flare are evident, but the separation of the two ribbons is absent. Furthermore, the detailed observations from IRIS show that the ribbons undergo special evolutions. For the first studied flare, the ribbon fragments (see Figure 2) “R2,” “R3,” and “R4,” successively swept a smaller region along different directions, indicating that the corresponding flare loops are enwound together. AIA observations confirm that the flare loops are enwound, e.g., shearing each other, in Figure 1(e). For the fourth flare, the two ribbon fragments move along the same direction (Figures 5(a) and (b)) with speeds of 10–20 km s\(^{-1}\), instead of separation. We imagine that only braiding flare loops can produce the two ribbons moving along the same direction, and the AIA observations (shear loops in Figure 4) support that scenario.

During the fourth flare process, the redshift velocities (10–30 km s\(^{-1}\)) at the middle region of the two ribbons are almost stable, suggesting that there is no violent upward (downward) movement enhancement in the lower atmosphere. In other words, the complex magnetic structures relevant to the flare do not undergo an ascending (descending) process, or the complex magnetic structures are stable and do not affect the flare. For comparison, the eruptive X-class flare on 2014 September 10 displayed different Doppler shifts, e.g., at the later phase of the flare, the redshift velocities at the post-flare loop position increased from 30 km s\(^{-1}\) to about 80–100 km s\(^{-1}\) (Figure 5(h)) in the transition region (Li & Zhang 2015), implying that the violent, downswamp-moving cool and dense chromospheric and transition regions condensate (Fisher et al. 1985) during the gradual phase. This study is only a preliminary step toward investigating the complex magnetic structures that confine solar flares. To further evaluate the effectiveness of these complex structures, a more robust study involving more events is needed.

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