

THE CONFINED X-CLASS FLARES OF SOLAR ACTIVE REGION 2192

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ABSTRACT

The unusually large active region (AR) NOAA 2192, observed in 2014 October, was outstanding in its productivity of major two-ribbon flares without coronal mass ejections. On a large scale, a predominantly north-south oriented magnetic system of arcade fields served as a strong top and lateral confinement for a series of large two-ribbon flares originating from the core of the AR. The large initial separation of the flare ribbons, together with an almost absent growth in ribbon separation, suggests a confined reconnection site high up in the corona. Based on a detailed analysis of the confined X1.6 flare on October 22, we show how exceptional the flaring of this AR was. We provide evidence for repeated energy release, indicating that the same magnetic field structures were repeatedly involved in magnetic reconnection. We find that a large number of electrons was accelerated to non-thermal energies, revealing a steep power-law spectrum, but that only a small fraction was accelerated to high energies. The total non-thermal energy in electrons derived (on the order of 10^{25} J) is considerably higher than that in eruptive flares of class X1, and corresponds to about 10% of the excess magnetic energy present in the active-region corona.

Key words: Sun: activity – Sun: atmosphere – Sun: flares – Sun: magnetic fields – Sun: photosphere – Sun: X-rays, gamma rays

1. INTRODUCTION

Coronal mass ejections (CMEs) and flares are interpreted to be different manifestations of a sudden instability and the associated release of magnetic energy in the solar corona. In general, they can occur independently of each other. Their association rate, however, strongly increases with the strength of the event. As can be inferred from Figure 1 of Yashiro et al. (2006), in about 10%, 40%, and 75% of *GOES* class C1-, M1-, and X1-flares, respectively, a CME association is found. Flares $\geq$ X2.5 have an association rate $>90\%$. Sometimes, however, the Sun shows striking deviations from this trend.

On 2014 October 17, active region (AR) NOAA 2192 appeared on the east limb of the Sun and developed into the largest AR since NOAA 6368 in 1990 November. In particular, the large size of NOAA 2192 was unexpected, as it occurred in the unusually weak solar cycle 24. During its passage across the visible solar disk, between October 17 and 30, it produced 6 X- and 30 M-class flares, as well as numerous smaller events. The *GOES* soft X-ray (SXR) flux of the six largest flares peaked on October 19 05:03 UT (X1.1), October 22 14:28 UT (X1.6), October 24 22:41 UT (X3.1), October 25 17:08 UT (X1.0), October 26 10:56 UT (X2.0), and October 27 14:47 UT (X2.0). A highly exceptional aspect of the flaring activity was the lack of eruptive events: none of the X-flares was accompanied by a CME.

In this Letter, we investigate NOAA 2192 in the period October 22–24 regarding its productivity of a series of large ($\geq$ M5) though confined flares and a single eruptive M4.0 flare. During this period, the AR was located within roughly 25° from disk center, so foreshortening effects were minimal. Additionally, we analyze in detail the X1.6 flare on October 22 which, in contrast to the other X-flares during the considered period, was also well covered by hard X-ray (HXR) data.

2. DATA AND METHODS

We use data from the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) on board the *Solar Dynamics Observatory* (*SDO*; Pesnell et al. 2012). In particular, 1700 Å (sampling the photosphere at the minimum temperature) and 1600 Å (picturing photospheric plus transition region emission) filtergrams were used for the analysis of flare ribbons. For a clear distinction of the low-atmosphere imprint of the four events under study, we use 1700 Å data. In this way, we avoid a contamination of the signal due to ejected material during the eruptive M4.0 flare (which, in the line of sight (LOS), overlaps with the actual flare ribbons that we aim to track). For detailed analysis of the flare ribbons and the energy deposited by non-thermal electrons during the X1.6 flare, we use 1600 Å images.

Short-term brightenings not related to flaring activity were removed by applying a 3 minute running-median filter to the image sequences (at a 1 minute cadence). These filtered images were used to track the location and time evolution of flare pixels. To identify flare pixels, we use the 99th percentile intensity of the entire series of filtered images as a threshold for detection. Importantly, the 99th percentile determines only the brightest pixels in a series of images in a particular wavelength due to its definition based on the relative occurrence of intensity values. Effects of blooming and saturated pixels around the flare peak time were minimized by requiring that a flare pixel had to be identified in at least five consecutive images.

The above data sets are complemented by *SDO*/Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) magnetic field data. The large-scale coronal magnetic field environment around NOAA 2192 is retrieved via the potential field source surface (PFSS) package available in *SolarSoftWare* (for details see Schrijver 2001; Schrijver & de Rosa 2003). It is based on a synoptic HMI magnetogram for Carrington Rotation 2156 and gives the current-free coronal magnetic field between $1.0 R_{\text{Sun}}$ and $2.5 R_{\text{Sun}}$. For a detailed analysis of the energetics involved in the X1.6 flare on October 22, the local coronal magnetic field

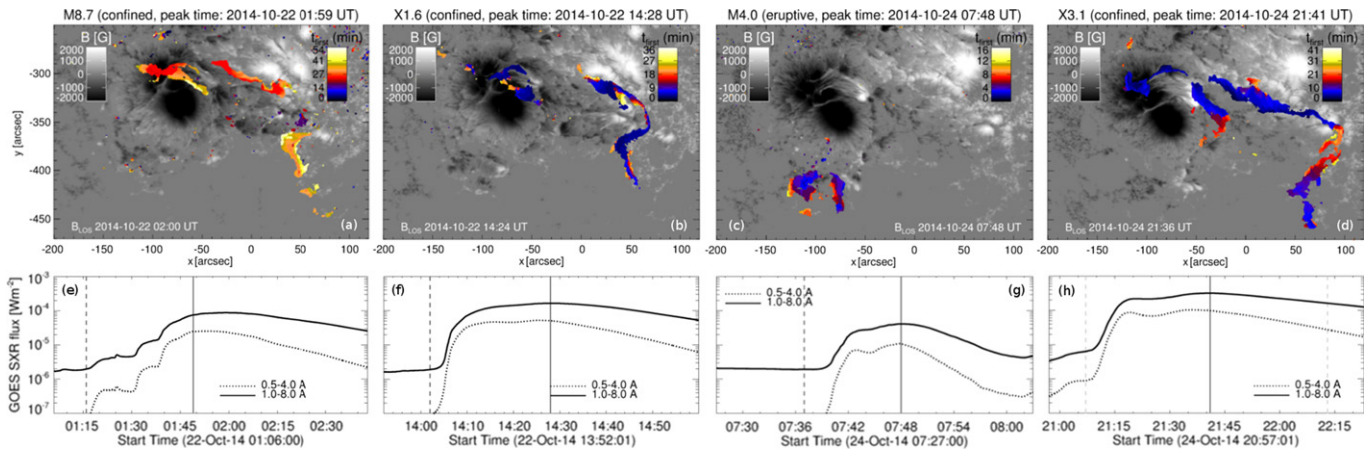


Figure 1. Top panels: flare ribbon progression associated with the (a) M8.7, (b) X1.6, (c) M4.0, and (d) X3.1 flare. The color indicates when a specific location was identified as a flare pixel for the first time in AIA 1700 Å images (given in minutes after the flare onset). The locations marked are when the identification as a flare pixel occurred between the start time and 10 minutes after the peak time of the respective flare. The grayscale background resembles the LOS magnetic field of NOAA 2192 around the peak time of the respective flare, scaled to ± 2000 G. Black and white refer to negative and positive polarity, respectively. Units are arcseconds from Sun center on October 23 12:00:00 UT. Bottom panels: *GOES* 0.5–4.0 Å (gray dotted) and 1.0–8.0 Å (black solid) SXR light curves of each flare. Vertical dashed and solid lines mark the start and peak time of the respective flare, respectively.

in and around NOAA 2192 is approximated by a nonlinear force-free (NLFF) field, following Wiegmann & Inhester (2010).

This flare was also well covered by the *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*; Lin et al. 2002). *RHESSI* X-ray images were reconstructed using the Clean algorithm (Hurford et al. 2002). Additionally, we use AIA 94 Å to trace the hot coronal flare plasma and ground-based H α filtergrams from Kanzelhöhe Observatory (KSO; Pötzi et al. 2014), which sample purely chromospheric layers.

All data were prepared using standard IDL mapping software and corrected for differential rotation.

3. RESULTS

3.1. Flare Ribbon Progression—Confined versus Eruptive

The bottom panels of Figure 1 show the *GOES* SXR light curves for the investigated flares on October 22 and 24. All of the confined flares (Figures 1(a), (b), and (d)) show gradual characteristics (an initial rise phase followed by a prolonged decay). The flare durations were significantly longer than that observed for the eruptive M4.0 flare (Figure 1(c)), in contrast to the previously reported impulsiveness of confined events (e.g., Yashiro et al. 2006; Cheng et al. 2011).

The top panels of Figure 1 show the locations covered by flare ribbons, determined from 1700 Å images. In the course of the confined flares under study (Figures 1(a), (b), and (d)), two major ribbon systems are discernible: a shorter one close to the main negative-polarity sunspot and a longer one residing in the extended positive-polarity part of the AR.

The color code indicates when a certain position was identified as a flare pixel for the first time. Both ribbons appear first near the center of the AR and grow southward in time. This picture is clearly dominated by a large number of pixels brightening for the first time during the impulsive phase of the flares, when the ribbons grew fastest. However, despite showing a period of fast growth in extent, no considerable lateral separation of the ribbons was observed. Strikingly, they showed a large separation ($\gtrsim 50$ Mm) already at the confined flares' onsets. For comparison, eruptive X-flares often show a

ribbon separation of a few Mm in the rising phase, up to some tens of Mm in the decay phase (e.g., Zhang & Golub 2003; Xie et al. 2009; Maurya & Ambastha 2010; Qiu et al. 2010). We point out that the presented findings are neither a consequence of the wavelength selected for analysis nor of the intensity threshold used to identify flaring pixels.

Only the M4.0 flare had an associated CME and showed a clearly different location and morphology of the flare ribbons (Figure 1(c)). They were populating an area south of the main negative polarity, a region in which large-scale coronal loops seen in extreme ultraviolet (EUV) images (not shown here) fan out rapidly with their apexes reaching large heights and thus appear to be open. To understand why the major flares were confined, whereas the M4.0 flare was eruptive, we study the associated magnetic field topology.

3.1.1. Large-scale Magnetic Field Topology

The magnetic field strength in sunspot umbrae usually ranges from 1000 G to 2000 G, rarely exceeding 2500 G, with the umbral field strength scaling with the sunspot area (Schad 2014). NOAA 2192 fits well into this trend given its umbral radius on the order of 10 Mm (as seen in AIA continuum images) and an LOS magnetic field magnitude of $\gtrsim 2600$ G in the negative-polarity umbra.

Figures 2(a)–(c) show aspects of a PFSS model centered on October 24 06:04 UT. In the close-up view in Figure 2(a), we outline the location of the confined flares' ribbons (large yellow circle). A comparison to Figure 2(b) shows that they were situated below an arcade of a strong field and all of them occurred in the AR core. This arcade, with apexes reaching up to the source surface (at $2.5 R_{\text{Sun}}$; Figure 2(c)), likely prohibited the development of associated mass ejections. To substantiate, we calculated the potential field in and around NOAA 2192 up to a height of $\approx 1.5 R_{\text{Sun}}$ using a fast-Fourier approach (Alissandrakis 1981) based on HMI LOS magnetic field data. We calculate the total magnetic flux in a vertical plane, oriented along the main polarity inversion line. Following Wang & Zhang (2007), we employ the flux, normalized to the length of the vertical plane, in the two height regimes $1.0\text{--}1.1 R_{\text{Sun}}$ (F_{low}) and $1.1\text{--}1.5 R_{\text{Sun}}$ (F_{high}). The

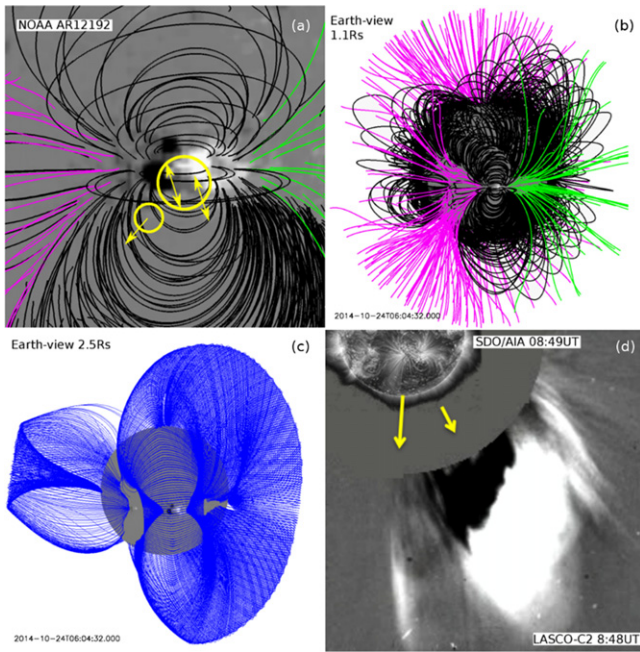


Figure 2. PFSS model result at 2014 October 24 06:04 UT. (a) Close-up view on the AR. Black lines indicate closed magnetic fields. Magenta and green lines mark open fields originating from locations of negative and positive polarity, respectively. The big yellow circle outlines the location of the high-energetic non-CME productive flares. The small yellow circle spots the location of the CME productive flare. Arrows within these circles indicate the approximate direction of motion of the flare ribbons. (b) Model field lines using a starting point for the field line calculation of $1.1 R_{\text{Sun}}$. (c) Model field lines with a starting point for the field line calculation just below the source surface, i.e., just below $2.5 R_{\text{Sun}}$. The grayscale background resembles the synoptic LOS magnetic field, scaled to ± 1200 G in (c) and to ± 600 G in (a) and (b). (d) LASCO-C2 image showing the CME associated with the M4.0 flare. An AIA 193 Å image shows hot flare plasma. Directions of the jet-like ejection and eruption are marked by a long and short yellow arrow, respectively.

former measures the strength of the inner core field and the latter are that of the overlying arcade field. We find $F_{\text{low}}/F_{\text{high}} \approx 0.3$, indicating a strong constraint of the overlying field.

Repeating the calculation at the time and location of the eruptive M4.0 flare indicates a similarly strong constraint of the overlying magnetic field. In contrast to the confined flares, it occurred at the edge of the strong arcade fields, close to apparently open field structures (as seen in the AIA 193 Å image; compare Figures 2(b) and (d)) toward which the flare ribbons progressed (Figure 2(a)). Indeed, AIA 193 Å images (not shown here) reveal jet-like signatures, followed by a CME directed to the southwest of the AR (the direction of motion is indicated in Figure 2(d)). This favors a scenario in which the eruptive M4.0 flare was related to the interaction with neighboring open fields, rather than due to a weaker constraint by the overlying field.

3.2. The Confined X1.6 Flare on October 22

3.2.1. Flare Evolution

Figure 3(a) shows the X-ray fluxes in the course of the flare. According to the GOES SXR light curve (black solid line), the impulsive phase of the flare started at 14:02 UT and the emission peaked at 14:28 UT. The RHESSI HXR >25 keV emission reveals two episodes of enhanced HXR bursts (around 14:06 UT and 14:23 UT).

Figure 4 shows the low-atmosphere and coronal emission during the impulsive phase of the flare. The AIA 1700 Å (Figures 4(a)–(c)) and KSO H α filtergrams (Figures 4(g)–(i)) show the evolution of bright flare ribbons. AIA 94 Å images (Figures 4(d)–(f)) show a hot coronal flare loop system that connects these ribbons.

RHESSI X-ray images in the 4–10 keV and 25–50 keV energy bands (yellow and cyan contours, respectively) indicate the location of thermal and non-thermal sources, respectively (shown on top of H α images in Figures 4(g)–(i)). Localized sources are seen already in the early phase of the flare (Figure 4(g)). The non-thermal sources are co-spatial with H α kernels, suggesting that these are footpoints of flaring loops, heated by non-thermal electron beams.

3.2.2. Energetics

To picture the evolution of the heated plasma and accelerated electrons, we show spatially integrated RHESSI X-ray spectra before the flare, during the rising phase, and at the times of two HXR peaks in Figures 3(b)–(e). These spectra were fitted with an isothermal and a power-law non-thermal thick-target model (Holman 2003). In the rise phase of the flare we used a second thermal component in order to achieve an acceptable goodness of fit (Figure 3(c)). The non-thermal electron distribution is steep during the entire flare. The hardest spectrum occurred during the flare peak, with an electron distribution index $\delta = 5.3$ (Figure 3(d)). This means that a small number of accelerated electrons reach high energies and explains why the X-ray flux increase is limited to energies <300 keV.

Following Emslie et al. (2012) and Feng et al. (2013), we fit the RHESSI spectra (with a cadence of 20 s) between 14:03 UT and 14:34 UT, in order to estimate the non-thermal energies in flare-accelerated electrons. We find that the non-thermal electrons carried $\approx 1.6 \times 10^{25}$ J. This is a factor of 10 larger than the energy in flare-accelerated electrons previously found for eruptive flares of GOES class X1 (e.g., Emslie et al. 2012). The uncertainty of such estimates in events with a large spectral index δ , however, may be as large as one order of magnitude.

We compare the non-thermal energy estimate to the free magnetic energy stored in the AR. Assuming a force-free pre- and post-flare corona, we approximate the local corona of NOAA 2192 using an NLFF model. The magnetic energy of the NLFF field in excess over that of a corresponding potential field gives an upper limit to the energy available for release during a flare. We consider a volume that covers the AR core (where the ribbons were observed) and extends up to ≈ 90 Mm, high enough to cover the reconnection site, which is presumably located somewhere below that height. Prior to as well as after the X1.6 flare, we find an excess energy of $\approx 1.5 \times 10^{26}$ J (with an estimated uncertainty of $\approx 10\%$). This is in agreement with the high magnetic energies generally found for ARs hosting major flares (see the review by Wiegmann et al. 2014). Given the estimated non-thermal flare energy, roughly 10% of the excess energy was carried away by accelerated electrons. At the same time, however, magnetic energy was again stored and resulted in a similar amount of excess energy after the flare, allowing for equally intense energy releases during the following major events.

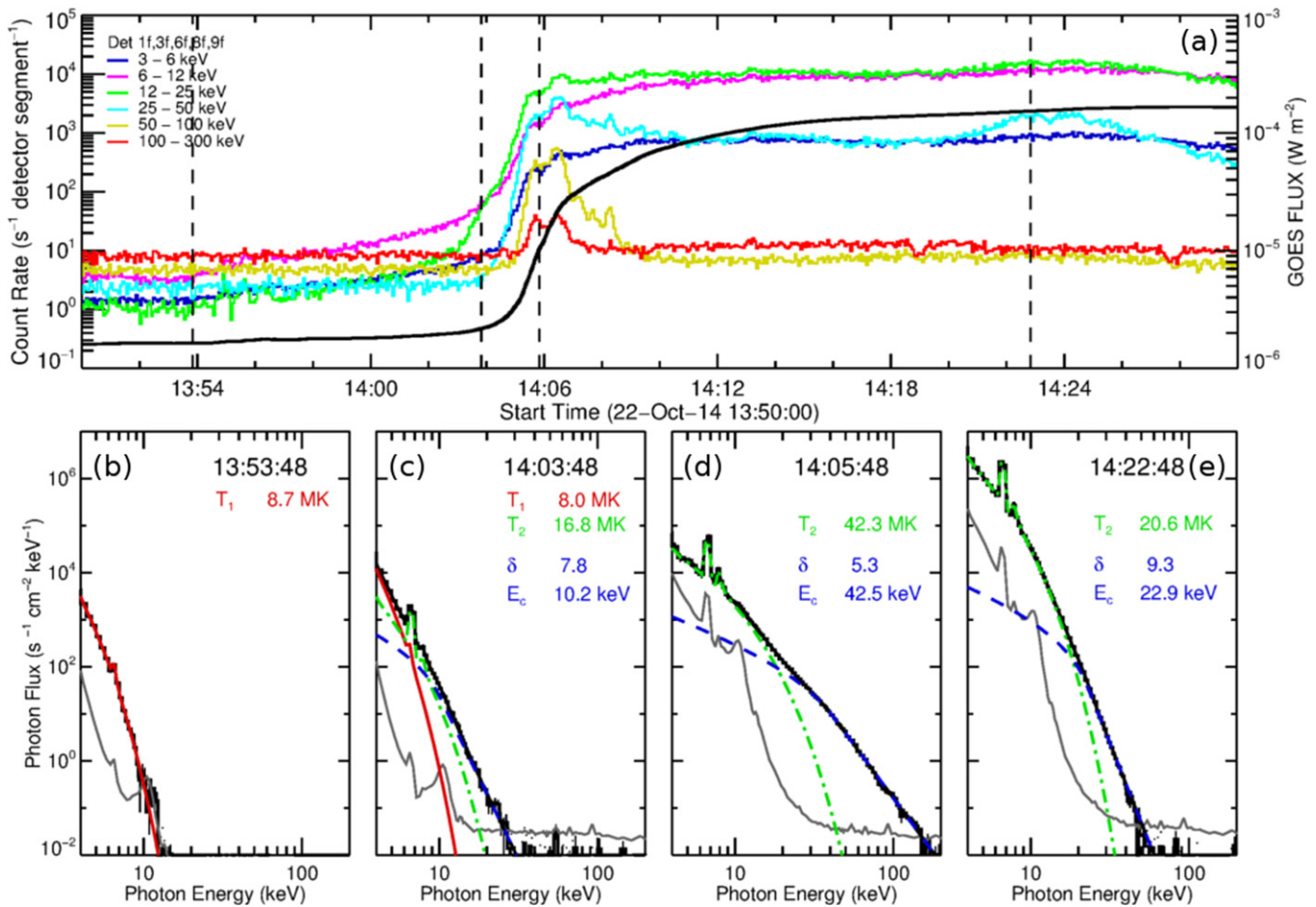


Figure 3. (a) *RHESSI* HXR count rates from 3 keV to 300 keV and *GOES* 1.0–8.0 Å SXR flux (black solid line) during the X1.6 flare on October 22. Vertical dashed lines mark selected times for which X-ray spectra are shown: (b) before the flare onset, (c) during the rising phase, and around the two HXR peaks at $\sim 14:06$ UT and $\sim 14:23$ UT (panels (d) and (e), respectively). Panels (b)–(e) show the corresponding X-ray spectra (black solid lines) and fitting results. Gray solid lines represent the X-ray background. Red solid and green dash-dotted lines show fitted isothermal components. Blue dashed lines mark the fitted non-thermal component. The fitting parameters used, including temperature T , electron distribution index δ , and low energy cutoff E_c , are listed accordingly.

3.2.3. Recurrent Brightening

Figure 5 shows the duration of brightness of the flare pixels tracked in AIA 1600 Å. It appears that locations successively closer to the center of the ribbons were bright correspondingly longer. The longest flare emission, lasting up to ≈ 30 minutes, was concentrated in five clusters (labeled C_1 – C_5). These locations nicely line up with the non-thermal *RHESSI* sources (cyan contours in Figure 4).

Importantly, C_1 – C_5 were associated with locations of recurrent brightenings, i.e., the re-energization of flare pixels (plus signs in Figure 5(a)). We interpret peaks detected in the 1600 Å light curves as representing re-brightening whenever these peaks were separated in time by more than 7 minutes (to allow for cooling effects) and if more than one peak occurred at the same location during the impulsive phase (between 14:02 and 14:28 UT). In Figures 5(b)–(f), we show characteristic light curves of locations situated in clusters C_1 – C_5 , respectively. Inspection of the light curves reveals that the first intensity peak occurred in the early impulsive phase (before $\sim 14:10$ UT), followed by another (sometimes even more pronounced) peak after $\sim 14:20$ UT. Note that these periods of re-brightening are tightly associated with the two episodes of HXR bursts (Figure 3(a)). These findings evidence that magnetic field structures originating from the same narrow

region (within the AIA resolution of $\approx 1''.2$) were involved in multiple magnetic reconnection events.

4. DISCUSSION

NOAA 2192 showed exceptional flaring behavior. In particular, it produced a series of six confined X-class flares in a period of nine days without associated CMEs. So far, only Wang & Zhang (2007) reported five confined X-flares that originated from a single AR (in the course of two days). Using global magnetic field modeling, we find the cause of confinement in the form of a roughly north–south oriented arcade of a strong magnetic field, serving as a top and lateral confinement to the flaring in the AR core. This is also supported by the more remote location of an eruptive M-class flare, which occurred close to the open field that neighbored the strong and closed core field.

The flare ribbons observed during the confined major (M5.0 and larger) flares on October 22–24 exhibited a period of fast growth in extent but no considerable separation. This phenomenon was reported so far only for flares $< M5.0$ (Su et al. 2007). In addition, the separation of the flare ribbons was large (≈ 50 Mm) already at the flares' onsets, which suggests a reconnection site high in the corona. The associated SXR light curves classify the confined flares as long-duration events, as

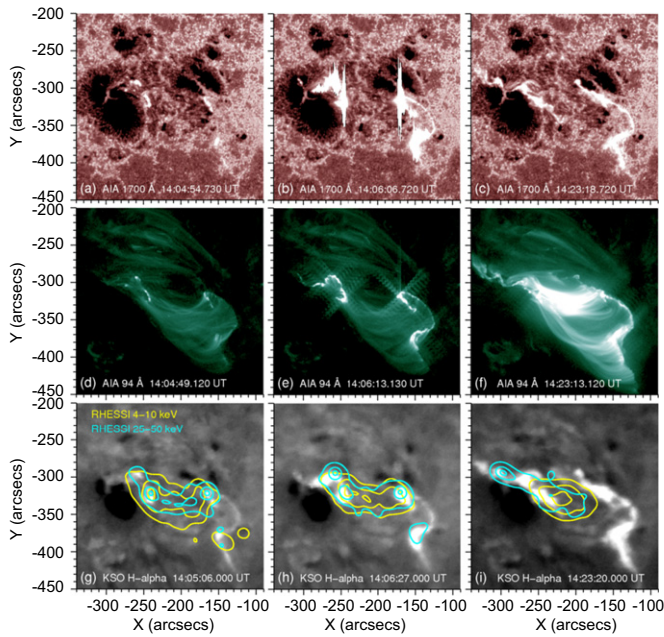


Figure 4. Coronal and low-atmosphere emission at three different times during the impulsive phase X1.6 flare on October 22. From top to bottom, ultraviolet (AIA 1700 Å), EUV (AIA 94 Å), and H α emission are shown. On top of the chromospheric H α images, in panels (g)–(i), *RHESSI* X-ray sources are shown. Yellow and cyan contours mark the emission in the 4–10 keV and 25–50 keV energy bands, respectively, and are drawn at [10, 50, 90]% of the respective maximum X-ray emission.

opposed to their suggested higher impulsiveness compared to eruptive events (e.g., Yashiro et al. 2006; Cheng et al. 2011).

Detailed analysis of the confined X1.6 flare on October 22 showed that the non-thermal electron distribution was very steep during the entire flare (compare with Battaglia et al. 2005) and that the total energy in electrons ($\approx 10^{25}$ J) was, for an X1-flare, unusually high (compare with Emslie et al. 2012). In accordance with previous studies, this shows such events to be efficient particle accelerators confined to the low corona (e.g., Klein et al. 2010). That also implies, however, that only a small fraction was accelerated to high energies out of the large number of particles accelerated at the reconnection site. A comparison of the non-thermal flare energy and the magnetic excess energy in the AR shows that about 10% of it was carried away by flare-accelerated electrons. Finally, we find re-brightening in flare pixels, providing evidence for the same magnetic field structures repeatedly involved in magnetic reconnection.

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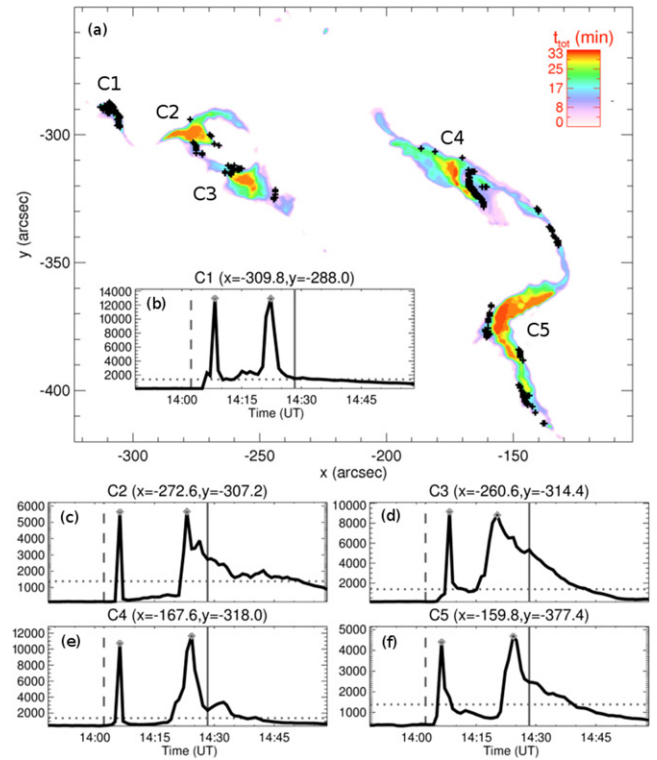


Figure 5. (a) Locations associated with flaring activity in the course of the X1.6 flare. Units are arcseconds from Sun center on October 22 at 14:04 UT. The color code indicates how long individual locations showed enhanced emissivity, between the nominal start (14:02 UT) and end times (14:50 UT). Areas that were bright for the longest time are concentrated in five clusters (labeled C₁–C₅). Plus signs mark locations associated with repeated brightening. Panels (b)–(f) depict typical AIA 1600 Å light curves at those locations. Vertical dashed and solid lines mark the start and peak times of the X1.6 flare, respectively. Horizontal dotted lines indicate the intensity threshold used to track flaring pixels.

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Erratum: “The Confined X-class Flares of Solar Active Region 2192” (2015, ApJL, 801, L23)

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In Thalmann et al. (2015), we calculated the horizontal magnetic flux through a vertical plane, oriented along the polarity inversion line in the photosphere below, in the two height regimes $1.0\text{--}1.1 R_{\text{Sun}}$ (F_{low}) and $1.1\text{--}1.5 R_{\text{Sun}}$ (F_{high}). The estimated ratio of these fluxes was wrongly indicated as $F_{\text{low}}/F_{\text{high}} \approx 0.3$, due to an unfortunate indexing problem in the underlying magnetic field model grid.

The actual value of the flux ratio, as inferred based on correct indexing within the model grid, is $F_{\text{low}}/F_{\text{high}} \approx 6$, with an uncertainty of about 10%. This does not alter the conclusion in Thalmann et al. (2015), as the correct result still indicates a strong confinement of the horizontal magnetic field overlying the analyzed flaring active region. However, now our result also lies well within the range of values found for the confined X-class flares analyzed in Wang & Zhang (2007).

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