EXPLOSIVE CHROMOSPHERIC EVAPORATION IN A CIRCULAR-RIBBON FLARE

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ABSTRACT

In this paper, we report our multiwavelength observations of the C4.2 circular-ribbon flare in active region (AR) 12434 on 2015 October 16. The short-lived flare was associated with positive magnetic polarities and a negative polarity inside, as revealed by the photospheric line-of-sight magnetograms. Such a magnetic pattern is strongly indicative of a magnetic null point and spine-fan configuration in the corona. The flare was triggered by the eruption of a mini-filament residing in the AR, which produced the inner flare ribbon (IFR) and the southern part of a closed circular flare ribbon (CFR). When the eruptive filament reached the null point, it triggered null point magnetic reconnection with the ambient open field and generated the bright CFR and a blowout jet. Raster observations of the Interface Region Imaging Spectrograph show plasma upflow at speeds of 35–120 km s⁻¹ in the Fe XXI λ1354.09 line (log T ≈ 7.05) and downflow at speeds of 10–60 km s⁻¹ in the Si IV λ1393.77 line (log T ≈ 4.8) at certain locations of the CFR and IFR during the impulsive phase of the flare, indicating explosive chromospheric evaporation. Coincidence of the single hard X-ray source at 12–25 keV with the IFR and calculation based on the thick-target model suggest that the explosive evaporation was most probably driven by nonthermal electrons.

Key words: Sun: chromosphere – Sun: corona – Sun: flares – Sun: X-rays, gamma-rays – techniques: spectroscopic

Supporting material: animations

1. INTRODUCTION

Solar flares are impulsive increases of emissions in various wavelengths from radio to hard X-ray (HXR) in the solar atmosphere (Benz 2008; Fletcher et al. 2011). Within tens of minutes to several hours, the free magnetic energies (10²⁹–10³² erg) accumulated before the flares are released and converted into kinetic and thermal energies via magnetic reconnection (Priest & Forbes 2000; Su et al. 2013). In the thick-target model, the accelerated nonthermal electrons (20–100 keV) are precipitated downward in the much denser chromosphere, leading to impulsive heating of the local plasma up to ~10 MK and rapid increase in HXR emissions via Coulomb collisions (Brown 1971; Cheng et al. 2010). When the heating timescale is much shorter than the radiative cooling timescale, the overpressure of the chromosphere pumps hot plasma into the newly reconnected coronal loops that emit strong emissions in extreme-ultraviolet (EUV) and soft X-ray (SXR), a process called chromospheric evaporation (Fisher et al. 1985a, 1985b, 1985c; Mariska et al. 1989; Emslie et al. 1992; Abbett & Hawley 1999; Allred et al. 2005, 2015). So far, it has been extensively investigated using both HXR imaging (Liu et al. 2006; Ning et al. 2009) and spectroscopic observations in Hα, EUV, and SXR wavelengths (Acton et al. 1982; Czyzakowska et al. 1999; Brosius & Phillips 2004; Young et al. 2013; Polito et al. 2015, 2016). Liu et al. (2006) studied the spatial evolution of the HXR emissions during the impulsive phase of an M1.7 flare. They found that the HXR emission centroids move from the loop top at speeds of hundreds of kilometers per second, which is indicative of continuous chromospheric evaporation as a result of the deposition of electron energies.

Chromospheric evaporation occurs when the input energy flux exceeds the critical value (≈10¹⁰ erg cm⁻² s⁻¹). Plasma upflows at speeds of hundreds of kilometers per second are observed in the emission lines formed in the coronal temperatures, while downflows at speeds of tens of kilometers per second are observed in the emission lines formed in the transition region and upper chromosphere (Brosius & Phillips 2004; Milligan et al. 2006b). The total momentum of upflowing plasma is approximately equal to that of the downflowing plasma or chromospheric condensation (Fisher 1987; Canfield et al. 1990). Otherwise, gentle evaporation takes place, accompanied by upflows at speeds of tens of kilometers per second in all emission lines (Milligan et al. 2006a; Sadykov et al. 2015). Recently, Reep et al. (2015) investigated the importance of electron energy on the two types of evaporation. They found that the threshold between explosive and gentle evaporation is not fixed at a given beam energy flux. Instead, it depends strongly on the electron energy and duration of heating. Occasionally, conversions from impulsive type to gentle type or from gentle type to explosive type are observed in different phases of flares (Brosius 2009; Li et al. 2015). Apart from the nonthermal electrons, thermal conduction also plays a role in driving chromospheric evaporation (Zarro & Lemen 1988; Battaglia et al. 2009; Zhang & Ji 2013), which has been explored in magnetohydrodynamic (MHD) numerical simulations (e.g., Yokoyama & Shibata 1998; Brannon & Longcope 2014; Longcope 2014). Reep & Russell (2015) discovered that Alfvénic waves, propagating from the corona to the chromosphere, can also heat the upper chromosphere and produce explosive evaporation. To date, the dominant driving mechanism is still controversial (Wuelser et al. 1994; Raft et al. 2009). The successful launch of the Interface Region Imaging Spectrograph (IRIS) Q. M. Zhang would significantly enhance our understanding of the driving mechanism of flares.
Imaging Spectrograph (IRIS; De Pontieu et al. 2014) telescope opened a new era for the study of flare dynamics. Evidences of electron-driven chromospheric evaporations have been reported using state-of-the-art observations of IRIS (e.g., Battaglia et al. 2015; Graham & Cauzzi 2015; Li et al. 2015a, 2015b; Tian et al. 2015).

In the context of a standard flare and coronal mass ejection (CME) model (e.g., Shibata et al. 1995; Lin et al. 2004), there are two parallel flare ribbons where nonthermal electrons collide and heat the chromosphere, which are observed in the Ca II H, Hα, UV, and EUV wavelengths. Apart from the two ribbons, a particular type of flare ribbons, i.e., circular ribbons, exist (Masson et al. 2009; Reid et al. 2012; Wang & Liu 2012; Jiang et al. 2013; Liu et al. 2013; Sun et al. 2013; Yang et al. 2015; Zhang et al. 2015). They are always associated with the spine-fan configuration in the presence of the magnetic null point, which is a singular point where the magnetic field vanishes (\( B = 0 \); Lau & Finn 1990). The magnetic field \( \mathbf{B} \) near the null point can be expressed as the linear term \( \mathbf{B} = \mathbf{M} \cdot \mathbf{r} \), where \( \mathbf{M} \) is a Jacobian matrix with elements \( M_{ij} = \partial B_i / \partial x_j \) and \( \mathbf{r} \) is the position vector \((x, y, z)^T\) centered at the null point (Parnell et al. 1996). The divergence-free condition \((\nabla \cdot \mathbf{B} = 0)\) requires that the sum of the three eigenvalues equals zero (Zhang et al. 2012). The two eigenvectors corresponding to the two eigenvalues of the same sign determine the fan surface, which divides the space into two regions having a different connectivity. The third eigenvector corresponding to the third eigenvalue of the opposite sign determines the direction of spines passing through the null point. Magnetic reconnection and particle acceleration in null point reconnection regions have been explored in analytical studies (Prist & Titov 1996; Litvinenko 2004) and three-dimensional (3D) numerical simulations (Rosdahl & Galsgaard 2010; Baumann et al. 2013a, 2013b). The circular ribbons are believed to be intersections of the fan surfaces and the chromosphere. The central or inner ribbons within the circular ribbons are thought to be intersections of the inner spines and the chromosphere (Reid et al. 2012; Wang & Liu 2012). Sometimes, there are multiple flare ribbons owing to the extraordinarily complex magnetic topology of the active regions (ARs; Joshi et al. 2015; Liu et al. 2015).

So far, chromospheric evaporations in circular-ribbon flares have rarely been observed and investigated, especially by IRIS. Although significant improvements in understanding the chromospheric evaporations have been achieved, there are still open questions that need to be addressed: How are the circular-ribbon flares generated? Are there explosive or gentle chromospheric evaporations in circular-ribbon flares? What is the cause of evaporation? In this paper, we report the multi-wavelength imaging and spectral observations of the GOES C4.2 circular-ribbon flare in NOAA AR 12434 (S10E37), which is one of the homologous flares on 2015 October 16. Data analysis and results of the filament eruption and flare are shown in Section 2. Data analysis and results of the explosive chromospheric evaporations in the circular flare ribbon (CFR) and inner flare ribbon (IFR) are presented in Section 3. Discussion and a summary are given in Sections 4 and 5, respectively.

2. FILAMENT ERUPTION AND CIRCULAR-RIBBON FLARE

2.1. Observation and Data Analysis

The flare was observed by the ground-based telescope of the Global Oscillation Network Group (GONG) in Hα line center and by the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) aboard the Solar Dynamic Observatory (SDO) in 1600 Å and EUV wavelengths (94, 131, 171, 193, 211, 304, 335 Å). The photospheric line-of-sight (LOS) magnetograms were observed by the Helioseismic and Magnetic Imager (HMI; Scherrer et al. 2012) aboard SDO. The level_1 data from AIA and HMI were calibrated using the standard Solar SoftWare (SSW) programs aia_prep.pro and hmi_prep.pro, respectively. To locate where the nonthermal particles precipitate, we made HXR images using the CLEAN method with an integration time of 120 s at different energy bands of RHESSI (Lin et al. 2002). The images observed in Hα, UV, EUV, and HXR wavelengths were coaligned with an accuracy of \( \sim 0^\circ.6 \). The observing parameters of the instruments are summarized in Table 1.

2.2. Results

Figure 1 shows the 171 Å image observed by AIA and the LOS magnetogram observed by HMI at \( \sim 13:39 \) UT. The flare occurred in AR 12434, which is characterized by a large-scale coronal arcade. In panel (b), the inset colored image shows the close-up of the flare region, which is characterized by a central negative polarity (N) surrounded by the positive polarities (P). Figure 2 shows the temporal evolution of the flare in 304 Å. Before the flare, a very small filament, which is indicated by the arrows, resided in the AR (see panels (a)–(b)). As time goes on, the dark mini-filament activated and generated elongated, jet-like brightening at \( \sim 13:35 \). After 13:37:30 UT, the filament erupted impulsively and generated the C4.2 flare, which features a CFR (see the animations of panels (e)–(f)). Meanwhile, the cool filament was heated significantly. In panel (f), the brightest region in the southwest of CFR coincides with the single HXR source at 12–25 keV. The rising and expanding filament became a curtain-like, blowout jet after 13:39:30 UT. Moore et al. (2010) classified the coronal jets into the standard type and blowout type. The standard type has simpler morphology and can be explained by the magnetic emerging-flux model (Shibata et al. 1992). The blowout type, however, results from small-scale filament eruptions accompanied by rotating and/or transverse drifting motions (e.g., Pariat et al. 2009; Moore et al. 2013; Zhang & Ji 2014; Kumar et al. 2016). In our work, the jet not only propagated longitudinally but also underwent transverse drift from west to east. Interestingly, the brightening at the base of the jet propagated in the counterclockwise direction along the CFR. In panel (g), the contours of the positive and negative LOS magnetic fields are superposed with magenta and green lines, respectively. As mentioned above in Figure 1(b), the negative polarity (N) is surrounded by positive polarities (P), which strongly implies the existence of a magnetic null point and spine-fan configuration in the upper atmosphere (Zhang et al. 2012, 2015). The CFR is approximately copspatial with the positive polarities, while the IFR is approximately copspatial with the negative polarity. In panels (h) and (i), the short and bright IFR within the CFR is copspatial with the HXR source.
The evolution of the flare observed in Hα is displayed in the top panels of Figure 3 with lower resolution. The preexisting dark filament, which was ∼15″ away from the sunspot, remained stable until ∼13:35 UT. It erupted and generated the blowout jet and circular-ribbon flare (see the online animation). The filament eruption and flare were also evident in the other wavelengths of AIA with higher formation temperatures. The rest of the panels of Figure 3 demonstrate selected images observed by AIA.

In order to investigate the evolution of the blowout jet, we selected two slices in Figure 3 (h): S1 along the jet axis and S2 across the axis. The time-slice diagrams of S1 and S2 in 171 Å are displayed in the left and right panels of Figure 4, respectively. The jet started at ∼13:39 UT and propagated outward along the axis at a speed of ∼308 km s⁻¹. Meanwhile, the jet underwent transverse drifting motion from west to east at a speed of ∼87 km s⁻¹, which is much higher than the previously reported values (Moore et al. 2013).

In Figure 5, panel (a) shows the SXR light curves during 13:20–14:00 UT in 0.5–4 Å and 1–8 Å. The short-lived C4.2 flare had a lifetime of ∼15 minutes. It started at ∼13:36:30 UT, peaked at ∼13:42:31 UT, and ended at ∼13:51 UT. The HXR light curves at various energy bands (3–6 keV, 6–12 keV, 12–25 keV, 25–50 keV, 50–100 keV) are plotted with colored lines in panel (b). The peak times at HXR energy bands preceded the SXR peak time by 1–2 minutes, implying the Neupert effect (Ning & Cao 2010).

3. CHROMOSPHERIC EVAPORATION IN FLARE RIBBONS

3.1. Observation and Data Analysis

Fortunately, the flare was captured by the IRIS Slit-Jaw Imager (SJI) in 1400 Å and raster observation in the “sparse
synoptic raster” mode. Each raster had 36 steps from east to west and covered an area of $35.5' \times 181.5'$. The step cadence and exposure time were $\sim 9.4$ and 7.1 s, respectively. Each step had a spatial size of $\sim 0.166'$ and a spectral scale of $\sim 25.6$ mÅ pixel$^{-1}$ in the far-ultraviolet bands, which equals $\sim 5.7$ km s$^{-1}$ pixel$^{-1}$.

The sixth raster data of Fe XXI and Si IV lines during 13:37:29–13:43:00 UT were preprocessed using the SSW programs *iris_orbitvar_corr_l2.pro* and *iris_prep_despike.pro*. The Fe XXI line ($\log T \approx 7.05$) is blended with cold and narrow chromospheric lines, which should be identified and removed using the multi-Gaussian fitting method (Li et al. 2015a, 2016). The line centers and widths of these blended lines are fixed or constrained, while their intensities are tied to specific species in the adjacent spectral window. The raster observations in this study lacked the spectral window “1343,” which includes the tied line at H$_2$ 1342.77 Å. The two blended lines at 1353.32 and 1353.39 Å were too weak to contribute to the Fe XXI, so they were not considered in this fitting. The Si IV line ($\log T \approx 4.8$) is

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**Figure 2.** Snapshots of the EUV 304 Å images observed by AIA. The white arrows point to the dark filament, jet, CFR, and IFR. In panel (g), the contours of the positive and negative LOS magnetic fields are superposed with magenta and green lines, respectively. In panels (f) and (h), the contours of the HXR images with levels of 70%, 80%, and 90% of the maximum intensity are superposed with blue lines.

(An animation of this figure is available.)
an isolated line, which can be well fitted by the single-Gaussian function.

3.2. Results

The animation of Figure 6 shows the 1400 Å images observed by IRIS/SJI with extremely high resolution during 13:31:23–13:46:28 UT. The evolution of the flare is quite similar to that in 304 Å in Figure 2, featuring bright CFR and IFR with ultrafine structures. The intensity of CFR did not increase simultaneously, but in the counterclockwise direction. Like in EUV and Hα wavelengths, the single HXR source is exactly located at the IFR (see panel (g)). The two vertical dashed lines in panel (e) denote the starting and ending positions of the 36-step raster observation, exactly covering the flare and jet during the impulsive phase. Since the slit and CFR intersect in two places during the scan, we call the northern and southern intersections NCFR and SCFR,
respectively. A few selected points at the NCFR, SCFR, and IFR are displayed as green, blue, and magenta plus signs, respectively, in panel (f).

The IRIS spectral windows of Fe XXI and Si IV at three times are shown in the left and right panels of Figure 7, respectively. The spectra profiles and results of multi-Gaussian fitting of three points representative of NCFR, IFR, and SCFR are displayed in the left panels. The fitting results of Fe XXI spectra are drawn in turquoise lines. It is clear that the line centers of the three points are blueshifted compared with the rest wavelength of Fe XXI at 1354.09 Å (Li et al. 2015a, 2016), indicating upflows of superhot plasma. The spectral profiles and results of single-Gaussian fitting of the same points are demonstrated in the right panels. The spectra of a non-flaring region are used for determining the rest wavelength of Si IV (1393.77 Å). It is evident that the line centers of the three points are redshifted compared with the rest wavelength, indicating downflows of plasma with temperature of ∼0.063 MK.

The calculated Doppler velocities of the NCFR, SCFR, and IFR in Figure 6(f) are plotted with diamonds, crosses, and boxes with error bars in Figure 8, respectively. The simultaneous upflows at speeds of 35–120 km s\(^{-1}\) in the high-temperature line and downflows at speeds of 10–60 km s\(^{-1}\) in the low-temperature line suggest that explosive chromospheric evaporation took place in the CFR and IFR during the impulsive phase of the flare (13:39–13:43 UT).

4. DISCUSSION

4.1. How is the Circular-ribbon Flare Generated?

Owing to the rapid increases of spatial resolutions and observational data of the space-borne telescopes, more and more circular-ribbon flares have been observed and reported (e.g., Masson et al. 2009; Reid et al. 2012; Wang & Liu 2012). Joshi et al. (2015) studied the M7.3 flare as a result of sigmoid eruption in a large-scale fan-spine-type magnetic configuration on 2014 April 18. The flare consists of parallel ribbons and a large-scale quasi-circular ribbon. To explain the observational aspects, the authors use a multistep magnetic reconnection: tether-cutting reconnection for the formation and eruption of the sigmoid, standard reconnection in the wake of the erupting sigmoid for the parallel ribbons, and null-type reconnection for the quasi-circular ribbon and blowout jet, which is a 3D breakout-type eruption in nature and has been studied in the previous numerical simulations of flux rope eruptions and CMEs (Lynch et al. 2008, 2009).

In our work, the eruption could be understood as follows. First, the mini-filament became unstable and rose as a result of tether-cutting reconnection, magnetic flux emergence, or ideal MHD instability (Zhang et al. 2015), which is beyond the scope of this paper and will be the main topic of the next paper. The slow activation was accompanied by small-scale brightening and jet-like motion (see Figures 2(b)–(d)). The reconnection in the wake of the erupting filament generated the IFR and SCFR, which can be considered as two parallel ribbons (see Figure 2(e)). When the filament reached the null point, it reconnected with the ambient field and produced the blowout jet and bright CFR (see Figures 2(f)–(i)). The accumulated twist in the filament was transferred to the ambient open field during the magnetic reconnection (Pariat et al. 2009; Moreno-Insertis & Galsgaard 2013). This is consistent with the transverse drift of the jet and the sequential brightening of CFR in the counterclockwise direction (see Figures 4(b) and 6).
that the explosive evaporation was most probably driven by nonthermal electrons accelerated by the flare (see Figures 2, 3, and 6). It should be emphasized that the integration time of the HXR images is 120 s, which is longer than that in Battaglia et al. (2015). We have tried making HXR images using 60 s integration time and found that the time and location of the HXR source are the same. The HXR images, however, became more dispersive due to the lower photon count rate and signal-to-noise ratio.

In order to justify our conjecture of electron-driven evaporation, we made an HXR spectrum during the impulsive phase of flare. The 4-minute integration time (13:38–13:42 UT) is sufficient to get a higher signal-to-noise ratio and smaller error bars. The spectrum and results of two-component fitting are displayed in Figure 9. The spectra for the thermal component and power-law nonthermal component are shown with dotted and dashed lines, respectively. The thermal temperature \(T\) and emission measure are \(\sim 28\) MK and \(2 \times 10^{16}\) cm\(^{-3}\), respectively. The power-law slope or spectral index \(\gamma\) of the HXR photons is \(\sim 2.1\). Therefore, the electron spectral index \(\delta = \gamma + 1 = 3.1\). The total nonthermal power \(P_{\text{tot}}\) above a cutoff energy \(E_c\) is \(1.16 \times 10^{28} I_e (E_e/E_c)^{\gamma-1} \text{erg s}^{-1}\), where \(I_e\) denotes the photon count rate (Aschwanden 2004). For the C4.2 flare, assuming that \(I_e = 10^9\) photon s\(^{-1}\) cm\(^{-2}\) and \(E_c = E_i = 20\) keV, \(P_{\text{tot}}\) is estimated to be \(1.1 \times 10^{28}\) erg s\(^{-1}\). Considering that the area of the HXR source is in the range of \(2.6 \times 10^{17}\)–\(1.1 \times 10^{18}\) cm\(^2\) (see Figure 2(h)), the total nonthermal energy flux is \((1-4) \times 10^{10}\) erg s\(^{-1}\) cm\(^{-2}\), which is greater than the threshold for explosive chromospheric evaporation (Fisher et al. 1985b). Therefore, the explosive evaporation in our study is most probably driven by nonthermal electrons. Polito et al. (2015) studied the C6.5 flare on 2014 February 3 and found that blueshifted (>80 km s\(^{-1}\)) profiles of the Fe xxi appear at the very early phase of the flare and gradually decrease to \(15\) km s\(^{-1}\) in ~6 minutes, which is in agreement with the prediction of chromospheric evaporation by the 1D hydrodynamic model. In our study, the velocities of the upflow range from \(35\) to \(120\) km s\(^{-1}\), which is roughly consistent with the results of Polito et al. (2015). However, the raster observation of IRIS was in the “sparse synoptic raster” mode instead of the “sit and stare” mode on 2015 October 16, so that we cannot study the spectral evolution of the same flare location.

Although we did not carry out magnetic extrapolation based on the photospheric magnetograms since the AR was close to the limb, the CFR surrounding the IFR in Figure 2(g) and the HMI LOS magnetogram in Figure 1(b) strongly suggest the existence of a null point and spine-fan topology in the corona (Masson et al. 2009; Reid et al. 2012; Wang & Liu 2012; Joshi et al. 2015). Baumann et al. (2013b) studied the mechanism of particle acceleration in the coronal 3D null point reconnection region, finding that subrelativistic electrons are accelerated by a systematic electric field in the current sheet. The impact regions of the high-energy electrons in the chromosphere agree well with previous observations. In this work, we are not sure whether the electrons are accelerated by the electric field or not. Quantitative calculations are required in the future. Besides, explosive evaporation took place at certain locations (see Figure 6(f)), though the raster covered the whole CFR and IFR. There are credible redshifts in the Si iv line at the other locations of CFR. However, the intensities of the Fe xxi are too weak, and the uncertainties of velocities are too large. Magnetic

4.2. What is the Cause of Chromospheric Evaporation?

Chromospheric evaporation is an important process in flare dynamics and has been extensively investigated. Explosive chromospheric evaporation in two-ribbon flares have been observed and reported (e.g., Czyzewska et al. 1999; Battaglia et al. 2015; Graham & Cauzzi 2015; Li et al. 2015b; Tian et al. 2015). Li et al. (2015a) explored the relationship between HXR emissions and Doppler velocities caused by the explosive chromospheric evaporation in two X1.6 flares on 2014 September 10 and October 22. The correlations between the HXR emissions and Doppler shifts of Fe xxi and C i (log \(T\) \(\approx 4.0\)) suggest that the explosive evolutions in the flares are driven by electrons. Battaglia et al. (2015) studied the chromospheric evaporation of the X1.0 flare on 2014 March 29. They found that the locations of HXR footpoint sources were coincident with the locations of upflow in part of the southern ribbon during the peak of the flare. During the decay phase, the evaporation was probably driven by energy flux via thermal conduction. They concluded that electron beams may play a role only in driving the chromospheric evaporation during the initial phases of the flare. In our study, explosive evaporation took place not only in the CFR but also in the IFR. The single HXR source was cospatial with the IFR, meaning

![Figure 5. (a) SXR light curves during 13:20–14:00 UT in 0.5–4 Å (dashed line) and 1–8 Å (solid line). (b) HXR light curves at various energy bands. The two dotted lines denote the starting (13:37:29 UT) and ending (13:43:00 UT) times of the IRIS raster observation we used.](image)
reconnection and the particle acceleration mechanism are tightly related to the magnetic configuration, and the precipitation of nonthermal electrons along the CFR may not be uniform and isotropic (Rosdahl & Galsgaard 2010; Baumann et al. 2013b). The temperatures of the chromosphere at the other locations are probably raised to a few times $10^5$–$10^6$ K by the limited flux of electrons, which is far less than the formation temperatures of Fe xxi (~11 MK) and AIA 94 Å (>6 MK) in Figure 3(h).

5. SUMMARY

In this paper we report our multiwavelength observations of the C4.2 circular-ribbon flare by ground-based telescope, SDO/AIA, IRIS, GOES, and RHESSI on 2015 October 16 in AR 12434. The main results are summarized as follows:

1. The short-lived flare was associated with a negative magnetic polarity surrounded by positive polarities in the photosphere, which is strongly indicative of a magnetic
Figure 7. IRIS spectral windows (left column for “Fe XXI” and right column for “Si IV”) at 13:39:49 UT (top row), 13:41:07 UT (middle row), and 13:42:13 UT (bottom row). In each panel, the black curve is the spectra at the location marked by the red horizontal line. In the left panels, the red curves represent the results of multi-Gaussian fitting, and the turquoise profiles are Fe XXI. The rest wavelength (1354.09 Å) is labeled with turquoise vertical ticks. The 10 blended lines are labeled with blue vertical ticks in panel (c). In the right panels, the red curves represent the results of single-Gaussian fitting. The orange curve is the spectra for the nonflaring region, which is used for determining the rest wavelength of Si IV, i.e., 1393.77 Å.

Figure 8. Doppler velocities of the downflow derived from the Si IV λ1393.77 line and upflow derived from the Fe XXI λ1354.09 line for the NCFR (diamonds), IFR (boxes), and SCFR (crosses). The error bars of the velocities are indicated.

Figure 9. Results of RHESSI spectral fitting during 13:38–13:42 UT on 2015 October 16. The data points with horizontal and vertical error bars represent the observational data. The spectra for the thermal component and power-law nonthermal component are shown with the dot-dashed and dashed line, respectively. The sum of both components is shown with the thick solid line. The integration time and values of fitted parameters, including the thermal temperature ($T$), emission measure (EM), and power-law index ($\gamma$), are displayed.
null point and the fan-spine configuration in the corona. A mini-filament residing in the AR erupted, generating the IFR and SCFR, which can be considered as a pair of parallel ribbons.

2. When the filament reached the null point, it triggered magnetic reconnection, with the ambient open field near the null point, and generated the closed CFR and a blowout jet. The IFR and CFR were copatial with the negative polarity and positive polarities. The CFR brightening was sequential in the counterclockwise direction in the IRIS/SJI images. The blowout jet moved along the axis at a speed of $\sim 308 \text{ km s}^{-1}$. Meanwhile, it drifted from west to east across the axis at a speed of $\sim 87 \text{ km s}^{-1}$.

3. During the impulsive phase of the flare, there was plasma upflow in the hot Fe XXI line at speeds of 35–120 km s$^{-1}$ and downflow in the cool Si IV line at speeds of 10–60 km s$^{-1}$ in the IFR and CFR, indicating explosive chromospheric evaporation during the impulsive phase of the flare.

4. The IFR was copatial with the single HXR source at 12–25 keV. Calculation based on the thick-target model indicates that the explosive evaporation was most probably driven by nonthermal electrons. Whether the electrons were accelerated by the electric field in the current sheet during the magnetic reconnection is still unclear. Additional case studies combined with 3D numerical simulations are required in the future.

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