OBSERVATIONAL EVIDENCE OF ELECTRON-DRIVEN EVAPORATION IN TWO SOLAR FLARES

D. Li\textsuperscript{1,2}, Z. J. Ning\textsuperscript{1}, and Q. M. Zhang\textsuperscript{1}

\textsuperscript{1}Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, CAS, Nanjing 210008, China; lidong@pmo.ac.cn.
\textsuperscript{2}University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

We have explored the relationship between hard X-ray (HXR) emissions and Doppler velocities caused by the chromospheric evaporation in two X1.6 class solar flares on 2014 September 10 and October 22, respectively. Both events display double ribbons and the Interface Region Imaging Spectrograph slit is fixed on one of their ribbons from the flare onset. The explosive evaporation events were detected in these two flares. The coronal line of Fe xxi 1354.09 Å shows blueshifts, but the chromospheric line of C i 1354.29 Å shows redshifts during the impulsive phase. The chromospheric evaporation tends to appear at the front of the flare ribbon. Both Fe xxi and C i display their Doppler velocities with an “increase-peak-decrease” pattern that is well related to the “rising-maximum-decay” phase of HXR emissions. Such anti-correlation between HXR emissions and Fe xxi Doppler shifts and correlation with C i Doppler shifts indicate the electron-driven evaporation in these two flares.

Key words: line: profiles – Sun: flares – Sun: UV radiation – Sun: X-rays, gamma rays – techniques: spectroscopic

1. INTRODUCTION

Solar flares are drastic explosive phenomena on the Sun. They are able to release a huge amount of energy (∼10\textsuperscript{33} erg) in a typical timescale of tens of minutes. Based on the standard model, the flare energy is transferred from the magnetic energy. Magnetic reconnection is thought to be the primary energy release mechanism that heats the plasmas and accelerates the bi-directional nonthermal electrons in the solar atmosphere. This is known as the CSHKP model (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976). These nonthermal electrons that are guided by the reconnected magnetic field lines, not only travel to the interplanetary space but also precipitate into the lower corona and upper chromosphere, where they lose energy producing radiation through Coulomb collisions with the denser medium. This has been known as the “thick-target” model for the hard X-ray (HXR) emission (Brown 1971; Syrovatskii & Shmeleva 1972). Observations show that only a small fraction of the energy is lost through extreme-ultraviolet (EUV) radiation (Emslie et al. 1978; Milligan et al. 2014; Milligan 2015). The bulk of the energy heats the local chromospheric material rapidly up to a temperature of ∼10 MK. Then, the resulting over-pressure can drive the mass flow upward along the loop at speeds of a few hundred kilometers per second. The hot plasmas fill the flaring loops in a process called “chromospheric evaporation” (Brown 1973; Acton et al. 1982; Fisher et al. 1985a, 1985b; Liu et al. 2006; Ning et al. 2009; Ning & Cao 2010; Zhang & Ji 2013; Milligan 2015), resulting in soft X-ray (SXR) emission rising up. Substantial evidence of chromospheric evaporation has been reported in X-ray (e.g., Liu et al. 2006; Ning et al. 2009; Ning & Cao 2010, 2011; Ning 2011; Nitta et al. 2012; Zhang & Ji 2013), EUV (e.g., Doschek et al. 1980, 2013; Feldman et al. 1980; Antonucci et al. 1982; Ding et al. 1996; Milligan et al. 2006a, 2006b; Teriaca et al. 2006; Milligan & Dennis 2009; Chen & Ding 2010; Veronig et al. 2010; Li & Ding 2011; Veronig et al. 2015). Spectral images exhibit that the blueshifts tend to appear at the outside of the flare ribbons (Czykowska et al. 1999; Li & Ding 2004). Evaporation materials with high temperatures rise upward to disturb the coronal plasma, which results in the radio emission suddenly being suppressed on the radio dynamic spectra, especially at the decimeter range. A high-frequency cutoff drifting to a lower frequency is thought to be the signature of chromospheric evaporation (Aschwanden & Benz 1995; Karlicky 1998; Ning et al. 2009).

From the observations, there are two types of chromospheric evaporation. Evaporation is said to proceed “gently” when the chromosphere plasma lose energy via a combination of radiation and low-velocity hydrodynamic expansion. Emission lines formed at a temperature characteristic of the atmosphere from the chromosphere through the transition region to the corona all appear blueshifted (Milligan et al. 2006b; Brosius 2009; Raftery et al. 2009; Li & Ding 2011). Evaporation is regarded to proceed “explosively” when the chromosphere is unable to radiate energy at a sufficient rate and consequently expands at high velocities into the overlying flare loops. The overpressure of evaporated material also drives low-velocity downward motion into the underlying chromosphere in a process known as “chromospheric condensation” (Wüller et al. 1994; Czykowska et al. 1999; Kamio et al. 2005; Del Zanna et al. 2006; Teriaca et al. 2006). In this case, emission lines formed at temperatures characteristic of the upper chromosphere and the transition region all appear redshifted, while hotter lines from the corona appear blueshifted (Fisher et al. 1985a, 1985b) and radio emissions (Aschwanden & Benz 1995; Karlicky 1998; Ning et al. 2009).
et al. 1985a, 1985b; Del Zanna et al. 2006; Milligan et al. 2006a; Brosius 2009; Raftery et al. 2009; Li & Ding 2011).
Spectral observations show the redshifted velocity of \( \sim 20-40 \text{ km s}^{-1} \), which is an order smaller than the blueshifted value (\( \sim 200 \text{ km s}^{-1} \)). This is because the plasma density of the underlying lower chromosphere is much higher than that of the overlying corona.

Up to now, there are two viewpoints about how to drive the evaporation in the literatures. One is electron driven, while the other is thermal conduction driven. The former emphasizes that the nonthermal energy of nonthermal electrons plays an important role in the evaporation (Fisher et al. 1985a, 1985b; Milligan & Dennis 2009; Tian et al. 2014b), while the latter focuses on the thermal energy directly driven (Fisher et al. 1985a; Falewicz et al. 2009). In this paper, using the observations from the Fermi Gamma-ray Burst Monitor (GBM), Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI), Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO), and the Interface Region Imaging Spectrograph (IRIS), we explore the relationship between HXR emissions and Doppler velocities caused by evaporation during the impulsive phase in two solar flares in order to detect the observational evidence of the electron-driven chromospheric evaporation.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Observations

Two X1.6 solar flares are selected to study in this paper. First, they are well covered by the IRIS (De Pontieu et al. 2014) spectral observations. IRIS slit is fixed on the flare ribbon during the impulsive phase, which gives us an opportunity to detect the whole history of Doppler velocities caused by evaporation. Second, HXR emissions are also well observed by Fermi (Meegan et al. 2009) or RHESSI (Lin et al. 2002). One event takes place in NOAA AR 12158 on 2014 September 10. It starts at 17:21 UT and reaches its maximum at 17:45 UT on the GOES SXR light curves. Another occurs in NOAA AR 12192 on 2014 October 22. It starts at 14:02 UT and peaks at 14:28 UT on the SXR emissions.
Figure 1 shows the SDO/AIA (Lemen et al. 2012) 131 Å images (a, c) and IRIS/SJI images (b, d) of these two flares. The contours on the AIA 131 Å images represent the line-of-sight magnetic fields from the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board SDO. The levels are set at 800 (purple) and −800 (orange) G, respectively. The IRIS slit is fixed along the solar north–south direction on one ribbon of 2014 September 10 flare. The cadence is 9.4 s. For the 2014 October 22 flare, the IRIS slit is along the 45° to the north–south direction. IRIS detects the flare ribbon in the “raster” mode. Each raster has eight steps (marked by the number on the SJI 1330 Å image). Each step has a cadence of 16.4 s and a distance of ~2″. Thus, each raster has a duration of ~131 s.

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Both events display the double ribbons at SJI 1400 Å or 1330 Å images, as shown in Figures 1(b), (d). The 2014 September 10 flare shows one short ribbon around the positive filed region, while another is long with a curved shape around the negative filed region. This long ribbon is dynamic and propagating toward the southeast direction, subsequently crossing the IRIS slit during the flare impulsive phase. Figure 2 gives the time evolution of this ribbon on the AIA 1600 Å images. The arrow marks the ribbon propagation direction. This ribbon also exhibits strong quasi-periodic pulsations (i.e., Li & Zhang 2015; Li et al. 2015). Similar to the 2014 September 10 flare, one ribbon of the 2014 October 22 flare is around the positive filed region, and the other ribbon at the negative filed region is detected by the IRIS slit during the flare impulsive phase.

### 2.2. Spectral Fitting

Figure 3 shows the IRIS spectral profiles of three windows at “1343” (a), “Fe ii” (b), and “O i” (c) for the 2014 September 10 flare. IRIS has a spectral scale of ~25.6 mÅ/pixel for these three windows. The spectral data first have been calibrated and processed with the routines of iris_orbitvar_corr_j2.pro and iris_prep_despike.pro in the solar software (SSW) package. The first routine is used to correct IRIS spectral image deformation caused by the spacecraft orbital variation (Tian 2015).
et al. 2014a; Cheng et al. 2015). The second one is a generalized despiking tool for IRIS data. It could identify and remove the bad pixels through the iterative approach. At the flare onset (i.e., 17:28:43 UT), the spectral window at “O i” is characterized by many narrow, bright emission lines from neutral and singly ionized species, as well as molecular fluorescence lines. These emission lines blend with the broad line of Fe xxi 1354.09 Å (seen also Tian et al. 2014b, 2015; Li et al. 2015; Polito et al. 2015; Young et al. 2015), which is a typical coronal line used to detect the chromospheric evaporation. However, these blending chromospheric emission lines must be extracted before determining the Fe xxi intensity. According to the characteristics of IRIS spectral data, three steps are followed.

First, determine the line centers and widths (FWHM) at the “O i” window, including blending lines and Fe xxi. There are seven blending lines of Fe xxi, including Fe ii 1353.07, 1354.06 Å, Si ii 1352.69, 1353.78 Å, C i 1354.29 Å, and two unidentified lines at 1353.40 and 1353.61 Å, such as are marked by the red vertical ticks (except for C i) in Figure 3(c). These lines are bright in the active regions, while Fe xxi is quiet. Therefore, their line centers and widths can be detected from the single-Gaussian fitting in the active regions. During the solar flare, their centers and widths are constrained in a range to do spectral fitting based on the previous observations (e.g., Curdt et al. 2001, 2004). Taking the emission line of Si ii 1352.69 Å, for example, its center and width during the flare are same as the values from the active regions but constrained, such as the line center at 1352.69 ± 0.102 Å (ranging from 1352.588 to 1352.792 Å), and the maximum width of 260 mA, as listed in Table 1. C i has the strongest emission among these seven lines. Previous studies (Doschek et al. 1975; Cheng et al. 1979; Mason et al. 1986; Innes et al. 2003a, 2003b; Tian et al. 2014b, 2015; Li et al. 2015), its line center is set as 1354.29 ± 0.102 Å for the flare spectral fitting. Its line center is set at the range of 1354.29 ± 0.26 Å for the flare spectral fitting.

Table 1. The Parameters of 15 Emission Lines at Three IRIS Spectral Windows

Based on the fact that Fe xxi is a broad line (see Doschek et al. 1975; Cheng et al. 1979; Mason et al. 1986; Innes et al. 2003a, 2003b; Tian et al. 2014b, 2015; Li et al. 2015), its line center is set at 1354.29 ± 1.28 Å, which almost covers the whole “O i” window, and its line width is assumed with a minimum value of 230 mA, as listed in Table 1.

Second, tie the blending line intensities from other similar isolated lines during the flare. Figure 3(c) shows the coronal line of Fe xxi 1354.29 Å blending with these seven emission lines for the 2014 September 10 flare. There is no way to determine their flare intensities only at the “O i” window. However, IRIS has the spectra at other windows, i.e., “1343” and “Fe xii.” They also have the emission lines that behave similarly to the blending lines at “O i” window, such as H2 1342.83 Å at the “1343” window, Si ii 1350.13 Å at the “Fe xxi” window, and Fe ii 1354.80 Å at the “O i” window. 

Figure 3. Three IRIS spectra windows (a) for “1343,” (b) for “Fe xii,” and (c) for “O i” at 17:28:43 UT for the 2014 September 10 flare. The black profiles are detected at ~64 Å along the slit positions (marked by the short horizontal line). The brown profiles represent the multi-Gaussian fitting. The turquoise profile is Fe xxi, the magenta profile is C i, and the green is the background. The other 13 emission lines used in this paper are labeled by vertical ticks.
Their intensities can be used to tie the intensities of the six blending lines at “O’I” window during the flare eruption, as listed in Table 1. This is because Si II 1352.69, 1353.78 Å at the “O’I” window have a similar behavior to Si II 1350.13 Å at the “Fe xi” window, and Fe II 1353.07, 1354.06 Å at the “O’I” window have a similar behavior to Fe II 1354.80 Å at “O’I” window, and Unknown 1353.40, 1353.61 Å have a similar behavior to H 2 1342.83 Å at the “1343” window during the flare. These three emission lines are isolated and their intensities can be determined by a single-Gaussian fitting.

Third, determine the line parameters of Fe xxii and C I during the flare using the multi-Gaussian fitting. Figure 3 gives the six blending lines (except for C I) and three isolated emission lines marked with the red vertical ticks at three IRIS spectral windows. Fe xxii and C I are shown by the turquoise and magenta profiles. There are also another four isolated and bright lines marked with blue vertical ticks, such as Unknown 1348.34, 1348.60, and 1349.65 Å at the “Fe xxii” window, and Fe II 1354.91 Å at the “O’I” window. In total, these 15 lines (i.e., H 2 1342.83 Å, Unknown 1348.34 Å, Unknown 1348.60 Å, Unknown 1349.65 Å, Si II 1350.13 Å, Si II 1352.69 Å, Fe II 1353.07 Å, Unknown 1353.40 Å, Unknown 1353.61 Å, Si II 1353.78 Å, Fe II 1354.06 Å, Fe XXI 1354.09 Å, C I 1354.29 Å, Fe II 1354.80 Å, Fe II 1354.91 Å) superimposed on a linear background are used to do the multi-Gaussian fitting at three IRIS spectral windows simultaneously, such as the “1343,” “Fe xxii,” and “O’I” windows. In our fitting method, both Fe xxii and C I have free intensities, almost free line centers and widths, as listed in Table 1. The six blending lines of Fe xxii have constrained positions and widths and tied intensities. The other seven isolated lines have constrained positions and widths, but free intensities. Figure 3 shows one example of such a multi-Gaussian fitting. The black profiles are the observational spectra at the positions of about 64″/7 (marked by a short orange line) on the slit for the 2014 September 10 flare. The brown profiles are 15 fitting lines and the green line is the background. In this case, the intensities, centers, and widths of the 15 lines can be measured by the multi-Gaussian fitting at any time and at any position along the IRIS slit. Figure 3 also shows that there are still some other unknown emission lines at these three spectral windows, such as 1342.09, 1344.08, 1348.03, 1350.75, 1352.02, 1355.64 Å. They are located at the edges of the spectral windows and do not affect the spectral fitting to detect Fe xxii and C I. Therefore, they are not used for the spectral fitting in this paper.

Figure 4 gives four examples of the multi-Gaussian fitting for the flares on 2014 September 10 (top) and October 22 (bottom), respectively. The short vertical lines represent the rest wavelengths of Fe xxii (turquoise) and C I (magenta). It is well known that Fe xxii is a hot coronal line with a formation temperature of about 11 MK (log T 7.05), which results in Fe xxii being absent on the quiet Sun. Therefore, the rest wavelength of Fe xxii is not determined from the quiet regions. Recent studies from IRIS observations show that Fe xxii has a rest wavelength range between 1354.08 and 1354.10 Å (e.g., Tian et al. 2014b, 2015; Graham & Cauzzi 2015; Polito et al. 2015; Young et al. 2015). In this paper, we use their average value of 1354.09 Å as Fe xxii the rest wavelength. C I is a typical chromospheric line with a formation temperature of around 107 K (log T 4.0; Huang et al. 2014), and its rest wavelength can be determined from the emissions at the quiet regions, as the dashed profile shown in Figure 4(b), which plots the spectral profile average with 10 pixels around the position marked by the short black line. The spectra between 1353.66 and 1354.68 Å around C I are shown. In this paper, C I has a rest wavelength around 1354.29 Å.

2.3. Fitting Parameters

Using the method mentioned above, the intensities, line centers, and widths of Fe xxii and C I can be determined from the multi-Gaussian fitting along the IRIS slit. Figure 5 shows the spacetime diagrams of the intensities (a, c) and Doppler velocities (b, d) of Fe xxii and C I from 17:12 to 17:58 UT for the 2014 September 10 flare. There are strong EUV line emissions at about 60°−80° and 35°−40° along the slit. These two regions correspond to two propagation fronts (around 120 and 100 arcsec along the slit at 17:26 UT) of the curved ribbon in Figure 2(b), and the north region is the flare ribbon marked by the arrow. The spectral profiles at two positions of 64″/7 and 60″/6 on the slit but three different time are given in Figures 3 and 4(a), (b). The 2014 September 10 flare ribbon starts to cross the IRIS slit at about 17:25 UT, although there are weak emissions from 17:12 UT. The flare ribbon front displays a narrow point at the beginning, then it expands rapidly to a wide range of ∼25″ after 17:40 UT along the slit. As mentioned before, this process suggests the flare ribbon propagation across the IRIS slit.

Doppler velocity is detected by the fitting line center separation from the rest wavelength, whatever Fe xxii or C I. Figure 5(b) shows that the flare ribbon starts blueshifts, then redshifts at coronal line of Fe xxii, which is due to the chromospheric evaporation at the beginning of the flare, then the hot materials fall back to the chromosphere along the flare loop after cooling. This is consistent with the standard flare model and previous findings (Czyzakowska et al. 1999; Li & Ding 2004), and the evaporation appears at the outer edge of the flare ribbon. On the other hand, the evaporation tends to appear at the front of flare ribbon. The evaporation speed can reach ∼230 km s−1, while the falling speed is ∼25 km s−1 in the corona. Figure 5(b) shows that the evaporation roughly has a timescale of more than 10 minutes. Figure 5(d) gives the spacetime diagram of C I Doppler velocities. Different from the coronal line of Fe xxii, the chromospheric line of C I exhibits redshifts all along the flare, indicating that the 2014 September 10 flare is the explosive evaporation. There is a velocity peak of C I at the same time as the Fe xxii blueshift. The velocity can reach ∼27 km s−1. After blueshift, Fe xxii displays a similar value of redshift to C I.

Same as Figure 5, Figure 6 gives the spacetime diagrams along the IRIS slit of the intensities and Doppler velocities of Fe xxii and C I for the 2014 October 22 flare. As noted earlier, this event is observed in “raster” mode with eight steps. Thus, we can get eight spacetime diagrams at eight step positions, respectively. Figure 6 just shows the spacetime diagram at the second step. In this case, the slit cadence is ∼131 (16.4 × 8) s. The spectral profiles at two positions of about 59″2 and 47″4 on the slit are shown in Figure 4 (bottom). Similar to the 2014 September 10 flare, this event is the explosive evaporation. The coronal line of Fe xxii displays blueshift at the ribbon onset, then redshift, while the chromospheric line of C I exhibits redshift during the whole flare. The evaporation speed can reach ∼145 km s−1, and the falling speed is around 20 km s−1. The evaporation timescale is roughly estimated more than 10 minutes.
3. RESULTS

In order to study the relationship between the HXR emission and the evaporation speed, Figure 7 plots the X-ray light curves and the time evolution of Doppler velocities at Fe XXI and CI for both events. The 2014 September 10 flare is well detected by Fermi, but was missed by RHESSI, which detects the 2014 October 22 flare. Figure 7(a) shows the GOES 1.0–8.0 Å flux (black dashed lines) and Fermi/GBM light curves at 5 energy channels, such as 4.6−12.0 keV, 12.0−27.3 keV, 27.3−50.9 keV, 50.9−102.3 keV, and 102.3−296.4 keV. They are detected by the n2 detector, whose direction angle to the Sun is stable (∼60°) before 17:45 UT, then its angle changes to the Sun to produce an X-ray peak, which is not real. There is a data gap after 17:54 UT. The time resolution of Fermi is 0.256 s, but becomes a higher value (0.064 s) automatically in the flare state. We rebin all the data into an uniform resolution of 0.256 s here, as shown in Figure 7(a). Figures 7(c), (e) give the time evolution of Fe XXI and CI Doppler velocities at two positions along the slit, i.e., at slit positions of 64°7 (orange) and 60°6 (purple) in Figures 3 and 4 (upper). As predicted by the explosive evaporation, the coronal line of Fe XXI exhibits the blueshifts, while the chromospheric line of CI displays the redshifts at the same interval. Fe XXI increases its blueshifts rapidly to the maximum, then gradually and monotonically decreases to zero, continuously turning toward the redshifts. There are two possible explanations for these redshifts. First, they may be due to the hot material falling to the chromosphere along the flare loop after cooling. Second, they could be the signatures of loop contracting as seen in many imaging observations of flare arcades (e.g., Wang 1992; Ambastha et al. 1993; Sui & Holman 2003; Li & Gan 2005, 2006; Ji et al. 2006, 2007; Zhou & Ji 2009; Liu et al. 2013; Ning 2013; Yan et al. 2013; Zhou et al. 2013; Kushwaha et al. 2015; Wang & Liu 2015). Similar to Fe XXI, CI increases its redshifts first to the maximum and then decreases to a stable state of about 24 km s−1. There are two different physical scenarios to explain CI redshifts. The explosive peak of CI redshifts could be due...
to chromospheric condensation corresponding the evaporation detected as Fe XXI blueshifts at the same intervals, while the redshifts of C I on the decay phase could be due to the material falling back to chromosphere or the loop contracting, which results into the redshifts, not explosive but stable. Fe XXI and C I show explosive peaks at the Doppler velocities, and the peak values can reach about $-200 \text{ km s}^{-1}$ and $27 \text{ km s}^{-1}$, respectively. Although the peak time is different from the positions on the slit, the Doppler velocities exhibit a similar explosive peak. This is because the flare ribbon expands with time. The dashed lines in Figure 7(c) give the three times of the standard deviation (3σ) of the Doppler velocities from the quiet intervals (black profiles). The pluses (“+”) mark the points where the speed values above 3σ and corresponding to the HXR peaks. Here, the evaporation timescale can be estimated from Fe XXI blueshifts. It is about 10 minutes for the 2014 September 10 flare, which is consistent with recent findings for the same flare (Graham & Cauzzi 2015; Tian et al. 2015). The pluses in Figure 7(e) mark the same points as that in Figure 7(c). After the blueshifts, Fe XXI becomes redshifts with a value of $\sim 24 \text{ km s}^{-1}$. Meanwhile, C I redshift velocity has a similar value ($\sim 24 \text{ km s}^{-1}$), indicating the material falling downward with a similar speed from the corona. The error bars of the multi-Gaussian fitting are displayed every 20 points with 2δ uncertainties in Figures 7(c), (e). The orange and purple colors are for two different positions on the slit, respectively. On the flare ribbon, the enhancement emissions result into the fitting speed errors decreasing to about 2 km s$^{-1}$ (i.e., $\delta = \sim 2 \text{ km s}^{-1}$). Same as Figures 7(a), (c), and (e), Figures 7(b), (d), and (f) show the light curves of X-ray, Fe XXI, and C I Doppler velocities for the 2014 October 22 flare, which is well detected by RHESSI. As mentioned before, this event is detected by IRIS in “raster” mode, and Figures 7(d) and (f) show the Doppler velocities at the position of the second step in each raster. Same as Figure 6, the time resolution is as low as 131 s. And the evaporation timescale of $\sim 11$ minutes is estimated from Fe XXI blueshifts. The error bars of the multi-Gaussian fitting are shown by every two points for each Doppler velocity.

Figure 7(a) shows that there are three impulsive HXR peaks ($>27.3 \text{ keV}$) as marked by “1,” “2,” and “3.” It is clear that the last two HXR peaks (“2” and “3”) are well correlated with the
Doppler velocity peaks at two distinct positions, as shown in Figures 7(c), (e), whatever Fe XXI or C I. In other words, both Fe XXI and C I exhibit a “increase-peak-decrease” pattern of their Doppler velocities, well correlated with the “rising-maximum-decay” phase at HXR emission. Considering the velocity direction, HXR light curves are anti-correlated with Fe XXI Doppler velocities, while correlated with C I Doppler velocities. This situation is well seen in the 2014 October 22 flare as well. There are two HXR peaks at the channel of 25 –50 keV, as marked by “1” and “2” in Figure 7(b). They are well correlated with the Fe XXI and C I Doppler velocity peaks at two distinct positions, as shown in Figures 7(d), (f).

Figure 8 plots HXR peaks at 27.3–50.9 (or 25–50) keV dependence on the Fe XXI and C I Doppler velocities for the 2014 September 10 and 2014 October 22 flares, respectively. As expected from the electron-driven evaporation model, we find an anti-correlation between HXR emissions and coronal line (Fe XXI) evaporation velocities, while correlation between HXR emissions and chromospheric line (C I) condensation velocities. The correlation coefficient above 0.7 indicates that the nonthermal electrons cause the HXR emissions and drive the explosive evaporation simultaneously after precipitating in the chromosphere. Figures 8(c), (d) show only four points used for the correlation of each HXR peak due to the low time resolution of the IRIS raster for the 2014 October 22 flare. For the peak “1,” the HXR emission at 25–50 keV starts an intensity as small as about 20 counts s⁻¹, then becomes more than one order larger after the maximum. That results in a single point at about 20 counts s⁻¹ of HXR emission in Figures 8(c), (d). The correlation coefficient will become larger if this point is omitted.

Figure 9 plots the two HXR peaks at higher-energy channels (such as 50.9–102.3 keV and 102.3–296.4 keV) dependence on Fe XXI and C I Doppler velocities for the 2014 September 10 flare. The similar anti-correlation between HXR emissions and coronal line (Fe XXI) Doppler shifts, while correlation between HXR emissions and chromospheric line (C I) Doppler shifts are found during the same interval. The higher correlation coefficients (>0.85) further confirm our results.
4. DISCUSSIONS

Using \textit{IRIS} spectral observations on the flare ribbon and HXR observations from \textit{Fermi} or \textit{RHESSI}, we investigate the relationship between HXR emissions and Doppler velocities during the explosive evaporation of two X-class solar flares on 2014 September 10 and October 22. Using the multi-Gaussian fitting, Doppler velocities of Fe XXI and C I are detected from \textit{IRIS} spectral observations. At certain positions on the slit, Fe XXI and C I display their Doppler velocities with a “increase-peak-decrease” pattern, which is well related to the “rising-maximum-decay” phase of HXR emissions. Consistent with previous findings (Fisher et al. 1985a, 1985b; Milligan & Dennis 2009; Brosius 2013; Tian et al. 2014b), we find a high anti-correlation between HXR emissions and coronal line Doppler shifts of Fe XXI, and a high correlation between HXR emissions and chromospheric line Doppler shifts of C I, indicating the electron beam-driven explosive evaporation in these two solar flares. Similar results are also found in a recent paper by Tian et al. (2015), who get a high correlation between Fe XXI blueshifts and a derivative of \textit{GOES} SXR for the 2014 September 6 and 10 flares.

As noted earlier, Figure 7 plots the Fe XXI and C I Doppler velocities at two distinct positions, respectively, which results in a good correlation with HXR peaks simultaneously. The peak time of Doppler velocities would be changed for various positions on the slit. In other words, Doppler velocities on the other positions are not well correlated with the HXR peaks at the same intervals. However, the time profiles of Doppler velocities at any positions exhibit a similar shape to that shown in Figure 7. We can still obtain the high correlations between Doppler velocities and HXR peaks after shifting an interval of Doppler velocity peaks. These intervals are different for the various positions along the slit, and it is an open question that a temporal correlation does not exist at these positions along the slit. Figure 7 just gives the Doppler velocities at two special positions on the slit. They do not need to shift with time to do the correlation in Figures 8 and 9. For example, the first peak of
the purple curve in Figure 7(e) is at 17:29 UT, and it could correspond well with the peak “2” in Fermi data if it is shifted an interval of about 1 minute. While the second peak at 17:33 UT is corresponding well with the HXR peak “3” without shifting. Tian et al. (2015) reported a time delay (∼0.5–2.0 minutes) for the larger correlation between the Fe XXI blueshifts and SXR derivative on 2014 September 10 flare. This delay should be caused by the spectral profiles at different positions along the IRIS slit. When the flare ribbon propagates toward the southwest and expands with time, the peak of Fe XXI blueshifts changes with the slit positions, as well as with the time (seen in Figures 2 and 5). In this paper, we fit all the spectra along the IRIS slit at all times to obtain the spacetime images of Doppler velocities and get the time evolution of Doppler velocities at any positions on the slit. On the other hand, both Fe XXI and C I exhibit redshifts on the flare decay phase, especially for the 2014 September 10 flare. As the cross (“×”) marked in Figures 7(c), (e), Fe XXI has a velocity of ∼24 km s⁻¹, while C I has a small peak. The spectral profile at this time is given in Figure 4(b), which shows strong emissions at Fe XXI and C I. At this position, Fe XXI and C I have line centers of about 1354.19 and 1354.40 Å and line widths of 524.33 and 76.96 mÅ. They show redshifts from their rest wavelengths. These redshifts of Fe XXI and C I could be caused by the material falling down or the loop contracting at the decay phase of the flares.

The rest wavelength of chromospheric line C I is set as 1354.29 Å, which is detected from the quiet Sun (seen in Figure 4(b)). This is consistent with recent studies from IRIS observations (Polito et al. 2015; Sadykov et al. 2015). However, as noted earlier, Fe XXI is a hot coronal line, which is absent on the quiet Sun. Therefore, we can not determine the rest wavelength of Fe XXI from the nonflaring spectrum. There are different line centers of Fe XXI in the literatures. The first value of 1354.1 Å for Fe XXI has been identified from the spectra of solar flares by Doschek et al. (1975). Then the rest wavelength of Fe XXI is between 1354.06 and 1354.12 Å (e.g., Cheng et al. 1979; Mason et al. 1986; Feldman et al. 2000).

Figure 8. Scatter plots of two HXR peaks (orange and purple) dependence on Doppler velocities of Fe XXI and C I for the 2014 September 10 (a, b) and October 22 flares (c, d). The correlation coefficients (cc) are given.
Innes et al. (2003a, 2003b; Wang et al. 2003). In this paper, the rest wavelength of Fe XXI is set to 1354.09 Å, and this value is similar to that in recent studies (Tian et al. 2014b, 2015; Graham & Cauzzi 2015; Polito et al. 2015; Sadykov et al. 2015; Young et al. 2015) about Fe XXI from IRIS spectral data. Considering the broad range of Fe XXI, the rest wavelength has an uncertainty of about ±0.03 Å, corresponding to the Doppler velocity of about ±6.6 km s$^{-1}$. The rest wavelength of Fe XXI is probably taken from the decay phase of the flare due to its stable emission, as the example of the 2014 September 10 flare. However, the wavelength value is ∼1354.19 Å (i.e., the cross (“×”) in Figures 7(c), (d)) at the decay phase of this flare, which is much larger than the rest wavelength in previous studies. It is a fact that the coronal line of Fe XXI is absent in the nonflare regions where the temperature is not hot enough. Therefore, the intensities and Doppler velocities of Fe XXI in Figures 5(a), (b) and 6(a), (b) outside the flare regions are invalid, they are fitting noises from the observational data. Same as the chromospheric line of C I, its Doppler velocities (Figures 5(d) and 6(d)) outside the flare regions should also be fitting noises from the observation data.

The multi-Gaussian fitting is used to determine the Doppler velocities of Fe XXI and C I in this paper. There are three sources of uncertainties to their Doppler shifts. First, as shown in Figure 7, the fitting errors are very large in the nonflare regions and become much less in the flare regions, no matter Fe XXI or C I. This error is mathematic from the fitting method. Second, the red wing enhancement or redshifted component of the cool lines (i.e., Fe II, Si II, and C I) could affect the identification of Fe XXI (Tian et al. 2015; Young et al. 2015). There is no way to exactly rule out these blending lines from Fe XXI at present time. Using tied intensities, line centers, and widths could be a better approach, as normally lines from the same ion or similar lines should have similar behaviors. Therefore, we constrained and tied these lines with the emission lines in other windows (seen in Table 1) to eliminate the influence of these cool lines. Third, the asymmetries of C I line should also affect the derived redshift of C I. Because the Gaussian fitting of such asymmetrical lines tends to

Figure 9. Same as Figure 8, but HXR emissions at 50.9–102.3 keV and 102.3–296.4 keV for 2014 September 10 flare.
underestimate the velocity of chromospheric condensation, especially for the optically thick lines, i.e., Mg II line (Graham & Cauzzi 2015), and the Hα line (Ding et al. 1995). A good way to determine the Doppler shifts from the asymmetric line is the bisector method (i.e., Ding et al. 1995; Graham & Cauzzi 2015), which could accurately determine the Doppler shift, i.e., especially the redshift for the asymmetrical C1 in our case. However, not the bisector, rather the Gaussian fitting is used in this paper because C1 is one of the multi-Gaussian fittings in our code, while the bisector method is a better way for the isolated line.

In this paper, we find the blueshifts of Fe xxi quickly increase from zero to the maximum (more than 200 km s$^{-1}$) before decreasing, which is different from Polito et al. (2015) finding that the evaporation speed shows a monotonic decrease once appearing at the flare ribbon. This would be because we take the whole history of the Fe xxi Doppler velocities during the impulsive phase of the flare, while Polito et al. (2015) only show the Doppler velocities after its maximum. On the other hand, their data are in “raster” mode, rather than “sit and stare” mode. The time resolution is not high. The 2014 October 22 flare in this paper is in “raster” mode, and has a lower time resolution than the 2014 September 10 flare. However, we can also detect the Doppler velocity increase before its maximum. The flare on 2014 September 10 is also studied by Graham & Cauzzi (2015) and Tian et al. (2015). Both of them found very clearly a monotonic decrease of the Fe xxi blueshifts, but no increase before the peak, as shown in Figure 13 in Tian et al. (2015). They also found the evaporation within about 9 minutes, from 17:32 UT to 17:41 UT, which is similar to our results. The 2014 September 10 is also studied by Graham & Cauzzi (2015) and has a lower time resolution than the 2014 September 10.

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