We investigate the relationship between the blueshifts of a hot emission line and the nonthermal emissions in microwave and hard X-ray (HXR) wavelengths in the precursor of a solar flare on 2014 October 27. The flare precursor is identified as a small but well-developed peak in the soft X-ray and extreme-ultraviolet passbands before the GOES flare onset, which is accompanied by a pronounced burst in microwave 17 and 34 GHz and in HXR 25–50 keV. The slit of the Interface Region Imaging Spectrograph (IRIS) stays on one ribbon-like transient during the flare precursor phase, which shows visible nonthermal emissions in Nobeyama Radioheliograph and RHESSI images. The IRIS spectroscopic observations show that the hot line of Fe xxI 1354.09 Å (log \( T \) ∼ 7.05) displays blueshifts, while the cool line of Si iv 1402.77 Å (log \( T \) ∼ 4.8) exhibits redshifts. The blueshifts and redshifts are well correlated with each other, indicative of an explosive chromospheric evaporation during the flare precursor phase combining a high nonthermal energy flux with a short characteristic timescale. In addition, the blueshifts of Fe xxI 1354.09 Å are well correlated with the microwave and HXR emissions, implying that the explosive chromospheric evaporation during the flare precursor phase is driven by nonthermal electrons.

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

1. Introduction

Chromospheric evaporation is a well-known process, which was first described by Neupert (1968), during a solar flare. This process occurs when the chromospheric materials are heated more quickly than they can radiatively cool (Fisher et al. 1985a). The heated materials expand rapidly upward into the low-density corona along the reconnecting magnetic field lines, and then those hot plasmas fill up the newly formed flare loops that can be seen in the soft X-ray (SXR) or extreme-ultraviolet (EUV) passbands (Liu et al. 2006; Ning & Cao 2010; Milligan 2015; Li et al. 2017a). Usually, the emission lines formed at a high temperature show blueshifts, which provide strong evidence for chromospheric evaporation (Czaykowska et al. 1999; Liu et al. 2009; Milligan & Dennis 2009; Brosius et al. 2016; Lee et al. 2017). Due to momentum balance, some materials move slowly downward into the high-density chromosphere, which is evidenced by the redshifts in the emission lines formed at a low temperature (Teriaca et al. 2006; Tian et al. 2015; Zhang et al. 2016a; Li et al. 2017b). Notice that the redshifts in cool emission lines might not be observed in some chromospheric evaporation (Milligan et al. 2006; Brosius 2009; Raftery et al. 2009). In high-density chromospheric regions, the energy is lost through Coulomb collision between the precipitating electrons and the ambient plasmas, producing hard X-ray (HXR) or microwave emissions (Brown 1971; Asai et al. 2006).

Chromospheric evaporation can be detected in multiple wavelengths, ranging from HXR (Liu et al. 2006; Ning 2011; Zhang & Ji 2013) through EUV/UV (Czaykowska et al. 1999; Li et al. 2015a; Tian & Chen 2018) to microwave (Aschwanden & Benz 1995; Ning et al. 2009) channels. In HXR or EUV imaging observations, the movement of material from the double footpoints to the loop top along the flare loops is considered to be the HXR/EUV signature of chromospheric evaporation (Ning & Cao 2010, 2011; Zhang & Ji 2013; Li et al. 2017a). On the dynamic spectra, the microwave emission is suddenly cut off in higher frequency and drifts to lower frequency, which is believed to be the radio signature of chromospheric evaporation (Aschwanden & Benz 1995; Karlicky 1998; Ning et al. 2009). In spectroscopic observations, Doppler shifts in the emission lines that formed at different temperatures are often used to study chromospheric evaporation. The speeds of hot lines formed in the corona are observed to be as fast as around 100–400 km s\(^{-1}\), while the speeds of cool lines that formed in the chromosphere or transition region are only about 10–50 km s\(^{-1}\) (Ding et al. 1996; Veronig et al. 2010; Tian et al. 2014; Brosius et al. 2016). This is because the plasma density in the underlying chromosphere or transition region is much larger than that in the overlying corona on the Sun (Fisher et al. 1985a; Doschek et al. 2013; Milligan 2015).

Chromospheric evaporation proceeds “explosively” when the input energy flux exceeds a critical value of \(~10^{38}\) erg s\(^{-1}\) cm\(^{-2}\) (Fisher et al. 1985a, 1985b; Zarro & Lemen 1988; Kleint et al. 2016). The hot lines in the corona appear as blueshifts, while the cool lines in the chromosphere or transition region appear as redshifts (Feldman et al. 1980; Del Zanna et al. 2006; Brosius & Holman 2010; Chen & Ding 2010; Brosius & Daw 2015; Tian et al. 2015; Lee et al. 2017). Meanwhile, chromospheric evaporation proceeds “gently” if the input energy flux is less than the critical value, and all the emission lines from the chromosphere through the transition region to the corona appear as blueshifts (Milligan et al. 2006; Brosius 2009; Raftery et al. 2009; Li & Ding 2011; Sadykov et al. 2015). It should be mentioned that the critical
value of the energy flux between the “explosive” and “gentle” chromospheric evaporation also depends on the other beam parameters (Fisher 1989), duration of heating (Reep et al. 2015), and nature of acceleration (Rubio da Costa et al. 2015). For example, explosive evaporation can be driven by stochastic acceleration even with very low energy flux. At present, three mechanisms have been proposed to explain chromospheric evaporation. The first one emphasizes that nonthermal electron beams accelerated by magnetic reconnection (or electron driven; e.g., Brosius 2003; Milligan & Dennis 2009; Tian et al. 2014, 2015). The second one is thermal conduction, which states that thermal energy can drive chromospheric evaporation directly (Fisher et al. 1985a; Falewicz et al. 2009). The last one is the dissipation of Alfvén waves (Reep & Russell 2016).

Chromospheric evaporation usually occurs during the impulsive phase of a solar flare (Brosius & Phillips 2004; Brosius & Holman 2007, 2010; Tian et al. 2015; Li et al. 2017a), as stated in the standard flare model (Carmichael 1964; Sturrock 1966; Hirayama 1974; Kopp & Pneuman 1976). It can also happen in the decay or gradual phase of a solar flare (Zarro & Lemen 1988; Czyzakowska et al. 1999; Li et al. 2012). However, chromospheric evaporation in the pre-flare phase is relatively rarely reported. In fact, before the GOES flare onset, the SXR light curve has started to rise slowly or even shown a small but well-developed peak, which is called the flare precursor (e.g., Bamba et al. 2013; Cheng & Ding 2016a; Benz et al. 2017; Li et al. 2017c; Shen et al. 2017). Sometimes, the flare precursor can be identified as a chromospheric brightening in EUV/UV images, which is thought to be related to the characteristic structure of the magnetic field (Bamba et al. 2013, 2017). Imaging and spectroscopic observations also show that various precursors could appear during the pre-flare phase, such as during the eruption and oscillation of the magnetic flux rope (Cheng et al. 2015; Cheng & Ding 2016a; Li et al. 2016b, 2017c; Zhou et al. 2016; Yan et al. 2017), coronal dimmings (Zhang et al. 2017), and upflows in active regions (Imada et al. 2014; Dudik et al. 2016; Woods et al. 2017), which suggest that flare precursors may play an important role in triggering solar flares. In this paper, we detect chromospheric evaporation manifested by blueshifts of the hot Fe xxi 1354.09 Å line and the cool Si iv 1402.77 Å line that exhibits an SXR/EUV peak during the flare precursor phase. We also find a good correlation with high coefficients of about 0.87–0.97 between the blueshifts and the microwave/HXR emissions that show up before the GOES flare onset.

2. Observations and Data Analysis

Our observations focus on the active region of NOAA AR12192 on 2014 October 27 between 00:01 UT and 00:06 UT. This active region is simultaneously observed by the Interface Region Imaging Spectrograph (IRIS; De Pontieu et al. 2014), the Atmospheric Imaging Assembly (AIA; Lemen et al. 2012) and Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO), the Nobeyama Radioheliograph (NoRH; Hanaoka et al. 1994), and the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI; Lin et al. 2002). Figure 1 shows the snapshots of this active region in AIA 1600 Å (a) and 335 Å (b), respectively. The contours are integrated from the RHESSI observations (i.e., detectors 3, 4, 5, 6, and 8) with the CLEAN algorithm between 00:25 UT and 00:26 UT in 6–12 keV (brown), 12–25 keV (turquoise), and 25–50 keV (blue), respectively. The red dashed line outlines the slit of IRIS, which is along a 45° angle to the north–south direction. Two short purple lines mark the location studied in this paper, which is contained in the purple “R1” box. Box “R2” outlines another EUV/UV bright region, and “R0” refers to the entire active region in panel (b).

Figure 2(a) shows the SXR light curves in GOES 1.0–8.0 Å (black solid) and 0.5–4.0 Å (black dashed) from 00:01 UT to 00:19 UT. A GOES M7.1 flare begins to burst out at 00:06 UT (i.e., flare onset), as indicated by the dashed vertical line. Prior to the GOES flare onset, a small SXR peak appears at around 00:04:40 UT. It is much more pronounced in GOES 0.5–4.0 Å than in GOES 1.0–8.0 Å, as indicated by the purple and black arrows. Notice that the GOES SXR fluxes come from the full solar disk. To determine if the SXR peak is related to the M7.1 flare, we use the spatially resolved SDO/AIA observations. Therefore, the EUV fluxes (purple lines in panel (a)) in AIA 335 Å, which are integrated from the regions of R0 (purple solid), R1 (purple dashed), and R2 (purple dotted), are plotted. Similar to the SXR light curves in GOES 1.0–8.0 Å and 0.5–4.0 Å, the EUV fluxes from the entire active region (R0) reveal a faint peak, and in particular, the EUV fluxes from the region of interest (R1) show a pronounced peak also at around 00:04:40 UT while the EUV fluxes from the other region (R2) do not exhibit a corresponding peak at that time. This gives observational evidence that the EUV/SXR peak emission before the GOES flare onset is mainly from the studied locations (R1) and related to our flare event. Moreover, the region R1 should also be the main flaring region, which is indicated by the RHESSI emissions from 00:25–00:26 UT around the flare peak time (see the contours in Figure 1(a)). All of these observational facts suggest that the SXR/EUV peak can be considered to be the flare precursor. Figure 2(b) gives the normalized fluxes between 00:01 UT–00:19 UT in non-thermal emissions from NoRH 17 GHz (black solid) and 34 GHz (black dashed), RHESSI 12–25 keV (purple), and also GOES 1.0–8.0 derivative (orange). As with the light curves in SXR 0.5–4.0 Å and EUV 335 Å, both the microwave and HXR fluxes exhibit a pronounced burst before the GOES flare onset, i.e., from ~00:03:30 UT to ~00:05:50 UT, as indicated by the black arrow.

IRIS performs this observation in “sit-and-stare” mode from 18:52:50 UT on October 26 to 08:23:08 UT on October 27 in 2014, covering the flare precursor. It points at a fixed center position of (608°, –287°) with a maximum field of view (FOV) of 120° × 119°, which overlays the region of R1. Figure 3 shows the multiwavelength images from SDO/AIA, SDO/ HMI, and IRIS/SJI at the peak time of the flare precursor. Here, the X-axis is perpendicular to the slit of IRIS, and the Y-axis is parallel to the slit of IRIS. These images have the same FOV of 60° × 60°, as marked by the red dotted diamond in Figure 1(a). Panels (a) and (b) show the intensity images in AIA 94 Å and 131 Å. The overlaid contours represent HXR emission in 25–50 keV (blue contours), and microwave emissions in the frequencies of 17 GHz (yellow contour) and 34 GHz (orange contours), respectively, which are integrated from 00:04 UT to 00:05 UT. Panel (c) displays the line-of-sight (LOS) magnetogram. Panel (d) gives the SJI 1330 Å image with the overplotted green contours taken from the AIA 1600 Å intensities, which are applied to co-align with the SJI
1330 Å image by cross-correlating (Cheng et al. 2015; Tian et al. 2016). We can see that the bright features from these two passbands match well, since they both contain the UV continuum emissions in the temperature-minimum region. Figure 3 indicates that two ribbon-like transients in SJI 1330 Å (panel (d)) are connected by some hot coronal loops visible in the AIA 94 Å and 131 Å images (panels (a) and (b)), which are rooted in the positive and negative magnetic fields, respectively (panel (c)). One of the ribbon-like transients is crossed by the slit of IRIS, as marked by the dashed vertical line. This location is also co-spatial with the nonthermal source, such as the HXR emission in 25–50 keV, and the microwave emissions in the frequencies of 17 GHz and 34 GHz.

The hot emission line of Fe XXI 1354.09 Å and the cool emission line of Si IV 1402.77 Å have been used in many spectroscopic studies to investigate chromospheric evaporation (e.g., Tian et al. 2014, 2015; Li et al. 2015b, 2017a, 2017b; Brosius et al. 2016; Zhang et al. 2016a, 2016b). It is widely accepted that the forbidden line of Fe XXI 1354.09 Å is a hot (log $T$ ~ 7.05) and broad emission line during solar flares (Doschek et al. 1975; Cheng et al. 1979; Mason et al. 1986; Innes et al. 2003a, 2003b). Meanwhile, IRIS spectroscopic observations show that Fe XXI 1354.09 Å is always blended with a number of cool and narrow emission lines, which are from neutral or singly ionized species. Those blended emission lines can be easily detected at the position of the flare ribbon, including known and unknown emission lines, such as the C I line at 1354.29 Å, the Fe II lines at 1353.02 Å, 1354.01 Å, and 1354.75 Å, the Si II lines at 1352.64 Å and 1353.72 Å, and the unidentified lines at 1353.32 Å and 1353.39 Å (e.g., Li et al. 2015a, 2016a; Polito et al. 2015, 2016; Tian et al. 2015, 2016; Young et al. 2015; Tian 2017). In order to extract the hot line of Fe XXI 1354.09 Å and the cool line of C I 1354.29 Å (log $T$ ~ 4.0; Huang et al. 2014), we apply a multi-Gaussian function superimposed on a linear background to fit the IRIS spectrum at the “O I” window (e.g., Li et al. 2015a, 2016a), which has been pre-processed (i.e., IRIS spectral image deformation, bad pixel despiking and wavelength calibration) with the standard routines in Solar Soft Ware (SSW; Freeland et al. 2000). In short, the line positions and widths of these blended emission lines are fixed or constrained, and their peak intensities are tied to isolated emission lines from similar species. More details can be found in our previous papers (Li et al. 2015a, 2016a). On the other hand, the cool line of Si IV 1402.77 Å (log $T$ ~ 4.8) at the “Si IV” window is relatively isolated, and it can be well fitted with a single-Gaussian function superimposed on a linear background (Li et al. 2014, 2017a). Using the relatively strong neutral lines (i.e., “O I” 1355.60 Å and “S I” 1401.51 Å), we also perform an absolute wavelength calibration for the spectra at the “O I” and “Si IV” windows, respectively (Tian et al. 2015; Tian 2017). Finally, the Doppler velocities of Fe XXI 1354.09 Å, C I 1354.29 Å, and Si IV 1402.77 Å are determined by fitting line centers removed from their rest wavelengths (Cheng & Ding 2016b; Guo et al. 2017; Li et al. 2017a). As the hot Fe XXI line is absent in the non-flaring spectrum, the rest wavelength for the Fe XXI line (i.e., 1354.09 Å) is determined by averaging the line centers of the Fe XXI profiles which were used in the previous IRIS observations (Brosius & Daw 2015; Polito et al. 2015, 2016; Sadykov et al. 2015; Tian et al. 2015; Young et al. 2015; Brosius et al. 2016; Lee et al. 2017), while the rest wavelengths for the C I and Si IV lines, i.e., 1354.29 Å and 1402.77 Å, respectively, are determined from their quiet-Sun spectra (Li et al. 2014, 2015a).

3. Results

Figure 4 shows the time evolutions of the line profiles from 00:01:14 UT to 00:09:04 UT at the IRIS windows of “O I” (a) and “Si IV” (b), and the zero velocity is set to the rest wavelengths of Fe XXI 1354.09 Å or Si IV 1402.77 Å, respectively. They are averaged at the positions between ~36.9 and
Along the slit of IRIS, as marked by the two short purple lines in Figure 3. The overplotted lines in panel (a) are the time series of the Doppler velocity (blue/red), line width (turquoise/orange), and line intensity (yellow/purple) in Fe XXI 1354.09 Å and C I 1354.29 Å, respectively, and the overplotted lines in panel (b) are the time series of the Doppler velocity (red), line width (orange) and line intensity (purple) in Si IV 1402.77 Å. To exhibit the time series clearly, we have multiplied some time series by a factor. The Doppler velocities of Fe XXI 1354.09 Å start to appear as a precursor burst at ~00:03:30 UT in the blueshifted wings and peak at ~00:04:40 UT, then disappear before the GOES flare onset, at ~00:05:50 UT, as shown by the green crosses (“x”). During the same time intervals, the Doppler velocities of Si IV 1402.77 Å also exhibit a faint precursor peak before the GOES flare onset, as marked by the yellow arrow. Notice that the precursor peak in FUV emission lines from IRIS spectroscopic observations agrees well with the EUV precursor peak in AIA 335 Å from the imaging observations (Figure 2).

To investigate the driving mechanism of this chromospheric evaporation before the GOES flare onset, we first choose nine points from the blueshifts of Fe XXI 1354.09 Å during the flare precursor phase, i.e., between 00:03:30 UT and 00:05:50 UT, as shown by the blue crosses in Figure 5(a). The error bars represent the uncertainty of the Doppler velocity from the multi-Gaussian fitting (see also Li et al. 2015a). Second, we choose nine nearby points from microwave (34 GHz: black) and HXR (25–50 keV: green, 1.0–8.0 Å derivative: orange) fluxes. NoRH, GOES, RHESSI and IRIS.

During the flare precursor phase, the line widths of both hot (Fe XXI 1354.09 Å) and cool (C I 1354.29 Å and Si IV 1402.77 Å) emission lines demonstrate a small precursor peak. This fact is mostly likely to reveal an energy release process during this explosive chromospheric evaporation, which is used to heat the local plasma. The enhancements of these line widths in both hot and cool emission lines might also be caused by nonthermal broadening during the flare precursor phase. On the other hand, the line intensities in both C I 1354.29 Å and Si IV 1402.77 Å show a pronounced precursor peak before the GOES flare onset. Meanwhile, the line intensity of Fe XXI 1354.09 Å also exhibits a faint precursor peak before the GOES flare onset, as marked by the yellow arrow. Notice that the precursor peak in FUV emission lines from IRIS spectroscopic observations agrees well with the EUV precursor peak in AIA 335 Å from the imaging observations (Figure 2).

Figure 2. Panel (a): GOES SXR light curves from 00:01 UT to 00:19 UT on 2014 October 27. The purple profiles are the normalized fluxes in AIA 335 Å from different regions (see Figure 1) on the Sun. The solid vertical line marks the onset time of the solar flare. Panel (b): normalized fluxes between 00:01 UT–00:19 UT in the NoRH microwave, RHESSI HXR, and GOES derivative channels.
have the time cadences of 1 s, 2.05 s, 4 s, and 16.2 s, respectively, which make them impossible to correlate one by one. Therefore, we use the same points with the closest time. Figure 5(a) shows that these points from different light curves are well correlated during the flare precursor phase, indicating that this chromospheric evaporation may be driven by nonthermal electrons. Figure 5(b) shows that the blueshifts of Fe XXI 1354.09 Å depend on microwave emissions in the frequencies of 17 GHz (diamond) and 34 GHz (square), and also HXR emissions in 25–50 keV (triangle) and the 1.0–8.0 Å derivative (circle) during the flare precursor phase, i.e., between 00:03:30 UT and 00:05:50 UT. As expected from the electron-driven model of chromospheric evaporation (see Li et al. 2015a, 2017a; Tian et al. 2015), a high correlation between the blueshifts of Fe XXI 1354.09 Å and nonthermal (microwave or HXR) emissions is found. For example, the correlation coefficients of 0.97/0.88 are detected between the Fe XXI 1354.09 Å blueshifts and the microwave 17/34 GHz emission, and a correlation coefficient of 0.88 is found between the Fe XXI 1354.09 Å blueshifts and the SXR 1.0–8.0 Å flux derivative. Such high correlation coefficients demonstrate that the electron beams which might be accelerated by magnetic reconnection (e.g., Kundu et al. 1994; Brosius & Holman 2007; White et al. 2003; Asai et al. 2013) drive the explosive chromospheric evaporation during the flare precursor phase (Tian et al. 2015; Brosius et al. 2016; Li et al. 2017a). Meanwhile, the microwave and HXR emissions observed in the NoRH and RHESSI images exhibit a pronounced brightening source that is co-spatial with the ribbon-like transient during the flare precursor peak, which gives additional evidence of electron-driven evaporation before the GOES flare onset (Veronig et al. 2010; Zhang et al. 2016b; Li et al. 2017b). On the other hand, we also plot the dependence of the blueshifts of Fe XXI 1354.09 Å on the redshifts of Si IV 1402.77 Å during the flare precursor phase, and obtain a high correlation coefficient of 0.84. This is consistent with previous findings during a solar flare (Li et al. 2015a, 2017a, 2017b; Tian et al. 2015), due to the fact that the redshifts of the

Figure 3. Multiwavelength images along the IRIS slit direction around the SXR precursor peak of the solar flare. The blue contours represent the HXR emissions from RHESSI; the levels are set at 70% and 90%. The yellow and orange contours are the microwave emissions from NoRH. The green contours represent the AIA 1600 Å intensities. The red dashed line outlines the slit of IRIS, and the two short purple lines mark the locations studied here.
cool emission line are caused by overpressure in the evaporated material, and should therefore exhibit a correlation with the blueshifts of the hot emission line. We note that such a high correlation coefficient is not found between the Doppler shifts of C I 1354.29 Å and Fe xxi 1354.09 Å, C I 1354.29 Å, and Si iv 1402.77 Å. The green symbols mark the points during the flare precursor phase, and the solid vertical line indicates the onset time of the solar flare.

To further understand the deposited energy flux of the precursor event during chromospheric evaporation, the X-ray spectra observed by RHESSI are also analyzed here. Figure 6 shows the X-ray spectra with error bars and their two-component (thermal and nonthermal) fitting results during the flare precursor phase, i.e., from 00:04:04 to 00:05:04 UT. The physical parameters such as the break cutoff energy ($E_c \approx 23 \pm 3$ keV) and the power-law index ($\gamma \approx 4.5 \pm 0.8$) are derived from the spectral fitting as well as the Chi-squared ($\chi^2 = 2.44$). The Chi-squared shows quite reasonable fitting with $\chi^2 < 3$ presented by Sadykov et al. (2015). Then we can estimate the total nonthermal power ($P_{\text{tot}}$) of the accelerated electrons from Equation (1) (Aschwanden 2005; Zhang et al. 2016b):

$$P_{\text{tot}} = 1.16 \times 10^{24} \gamma^2 \left(\frac{E_c}{E_1}\right)^{(\gamma - 1)},$$

where $I_1$ represents the photon count rates at energies of $E \geq E_c$, and $E_1$ denotes the lower cutoff energy. In our observations, $I_1 = \int_{E_1}^{E_c} \frac{dI}{dE} \approx 5.3 \times 10^7$ photon s$^{-1}$ cm$^{-2}$ (Aschwanden 2005). Assuming that $E_c = E_1$ (Aschwanden 2005; Zhang et al. 2016b), $P_{\text{tot}}$ is estimated to be about $(5.6 \pm 2.9) \times 10^{28}$ erg s$^{-1}$. Figure 3(a) shows the HXR sources with the blue contours set in the 70% and 90% of the local maximum at 25–50 keV. The HXR source areas are inside these two blue contours, and the values are estimated in the range of $2.2 \times (10^{17}–10^{18})$ cm$^2$. The projection effect is also considered here (e.g., Sadykov et al. 2015). Finally, the total nonthermal energy flux ($P_{\text{tot}}/A$) is estimated to be about $(2.5 \pm 1.3) \times (10^{16}–10^{17})$ erg s$^{-1}$ cm$^{-2}$, which is larger than the typical threshold of $\sim 10^{16}$ erg s$^{-1}$ cm$^{-2}$ for the impulsive evaporation (Fisher et al. 1985a, 1985b; Zarro & Lemen 1988). The received upper nonthermal energy flux derived from this precursor event is as high as that of an X1 flare i.e., $\sim 3.5 \times 10^{11}$ erg s$^{-1}$ cm$^{-2}$ (Kleint et al. 2016). However, a much higher energy flux ($\sim 1.5 \times 10^{13}$ erg s$^{-1}$ cm$^{-2}$) for another solar flare is reported (see Sharykin et al. 2017). Our result suggests a strong energy flux during the flare precursor phase. Meanwhile, the characteristic timescale could be estimated from the nonthermal pulse in the HXR and microwave emissions, which is about 60 s (Figures 2 and 6).
It is short and on the order of the typical timescale of explosive chromospheric evaporation (Zarro & Lemen 1988; Sadykov et al. 2015). All of these observational results further confirm an explosive chromospheric evaporation during the flare precursor phase.

4. Conclusions and Discussions

Using spectroscopic and imaging observations from IRIS, SDO, NoRH, RHESSI, and GOES, we investigate the temporal and spatial relationships between the blueshifts of Fe xxi 1354.09 Å and the nonthermal emissions in microwave 17/34 GHz and HXR 25–50 keV before a GOES M7.1 flare on 2014 October 27. First, a small but well-developed peak in the SXR and EUV passbands before the GOES flare onset is identified as a flare precursor. Second, the hot Fe xxi 1354.09 Å line exhibits blueshifts and the cool Si IV 1402.77 Å line shows redshifts during the flare precursor phase; the blueshifts and redshifts are correlated well with each other. Moreover, the total nonthermal energy flux in the flare precursor exceeds the critical value (Fisher et al. 1985a, 1985b), and it is characterized by a short timescale. All of these facts suggest that an explosive chromospheric evaporation occurs in this flare precursor. Third, the blueshifts of Fe xxi 1354.09 Å show a good correlation with the microwave/HXR emissions, implying that the explosive chromospheric evaporation is most likely driven by nonthermal electrons, although we cannot exclude a possible contribution from the heating of Alfvén waves (Reep & Russell 2016; Lee et al. 2017).

Although chromospheric evaporation has been investigated in a large number of studies before (e.g., Ding et al. 1996; Brosius & Phillips 2004; Milligan et al. 2006; Chen & Ding 2010; Zhang & Ji 2013; Tian et al. 2014; Brosius & Daw 2015; Lee et al. 2017; Li et al. 2017c), to the best of our knowledge, this is the first report of an electron-driven explosive evaporation during the SXR/EUV precursor before the GOES flare onset. We note that chromospheric evaporation has been detected during the EUV “precursor” peak by Brosius & Phillips (2004) and Brosius & Holman (2007, 2010). However, those EUV “precursors” actually showed up after the GOES flare onset, or during the solar flare. In addition, the locations of those EUV “precursors” seem to be remote from nonthermal emissions, due to the limited observations, such as of HXR sources (Brosius & Holman 2007, 2010). It is widely accepted that the precursor peak is an important phenomenon prior to a solar flare (Cheng & Ding 2016a; Bamba et al. 2017; Li et al. 2017c; Shen et al. 2017; Zhang et al. 2017). Therefore, the observational results presented here help us to better understand the initiation process of solar flares. Electron-driven evaporation is detected before the flare onset, which implies...
that magnetic reconnection has occurred and has accelerated the electrons prior to the solar flare. This is also supported by several other observations (e.g., Bamba et al. 2013; Li et al. 2016b; Bamba et al. 2017; Li et al. 2017b, 2017c; Shen et al. 2017). The pre-flare reconnection (usually weak, see Li et al. 2017c) may cause the strong magnetic reconnection and trigger the associated solar flare.

Although explosive chromospheric evaporation is observed before the GOES flare onset, its properties are similar to the explosive evaporation occurring during a solar flare in general. First, both evaporations show a similar temporal and spatial correlation between the blueshifts (or upflows)/redshifts (or downflows) of emission lines and the HXR or microwave fluxes/sources (Milligan & Dennis 2009; Veronig et al. 2010; Tian et al. 2015; Brosius et al. 2016; Zhang et al. 2016a; Lee et al. 2017; Li et al. 2017a). Second, the pre-flare evaporation here also tends to appear at the front of a ribbon-like transient, which agrees with previous findings that chromospheric evaporation appears outside of flare ribbons (Czaykowska et al. 1999; Li & Ding 2004; Li et al. 2015a; Tian et al. 2015). Our observations indicate that chromospheric evaporation either in the pre-flare phase or during the flare occurs in successively formed flare loops. There are also some tiny differences between the explosive chromospheric evaporation during the flare precursor phase and that in the impulsive phase of a solar flare (e.g., Tian et al. 2014, 2015; Li et al. 2015b; Brosius et al. 2016). For example, the redshifts of the cool C I 1354.29 Å line appear much more constant and flat during the flare precursor phase. They do not show a pronounced precursor peak that corresponds with the blueshifted peak in the hot Fe XXI 1354.09 Å line; this is usually not the case for the explosive chromospheric evaporation during the impulsive phase of a solar flare (see Li et al. 2015a).

The maximum speed of the Fe XXI 1354.09 line during the flare precursor phase is only \(\sim 60 \text{ km s}^{-1}\), which is less than previous findings during the flare impulsive phase (Tian et al. 2014, 2015; Brosius & Daw 2015; Li et al. 2015a, 2015b; Young et al. 2015; Lee et al. 2017). The low speed might be caused by the projection effect, since the precursor event occurred somewhat away from the solar disk center, i.e., \(\sim 10^\text{W40}\). In this case, a projection effect would be involved, which may affect the estimation of the local plasma velocity from the Doppler shift. However, it just affects the value of the Doppler velocity and does not change its direction (the nature of flows). In previous observations, the blueshifted speed of an explosive chromospheric evaporation during a solar flare was often larger than \(100 \text{ km s}^{-1}\) (Zarro & Lemen 1988; Sadykov et al. 2015; Kleint et al. 2016). However, the observed blueshift of Fe XXI 1354.09 Å is the lower limit of the local plasma upflow; the actual velocity should be larger. We also detect a pronounced redshifted pulse from the cool emission line in Si IV 1402.77 Å, indicating local plasma downflow. This is
similar to the simulations of the explosive heating model (Kostiuk & Pikelner 1975), which showed that a temperature region divides the solar atmosphere into redshifted and blueshifted parts (e.g., Livshits 1983; Kosovichev 1986; Liu et al. 2009), and the division temperature is ~1 MK. Moreover, the total nonthermal energy flux during the flare precursor phase is high enough, and its characteristic timescale is very short. All of these observational facts are well consistent with the explosive evaporation model (Fisher et al. 1985a, 1985b; Zarro & Lemen 1988; Reep et al. 2015; Kleint et al. 2016). In short, the projection effect does not change our main results (Sadykov et al. 2015). Our observations also indicate that the speed of evaporated materials during the flare precursor phase is possibly smaller than that during the flare impulsive phase.

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References

Asai, A., Kiyohara, J., Takasaki, H., et al. 2013, ApJ, 763, 87
Asai, A., Nakajima, H., Shimojo, M., et al. 2006, PASJ, 58, L1
Aschwanden, M. J. 2005, Physics of the Solar Corona (2nd ed.; Chichester: Praxis Publishing)
Aschwanden, M. J., & Benz, A. O. 1995, ApJ, 438, 997
Bamba, Y., Kusano, K., Yamamoto, T. T., & Okamoto, T. J. 2013, ApJ, 778, 48
Bamba, Y., Lee, K.-S., Imada, S., & Kusano, K. 2017, ApJ, 840, 116
Benjamin, C. B., Battaglia, M., & Gudel, M. 2017, ApJL, 292, 151
Brosius, J. W. 2003, ApJ, 586, 1417
Brosius, J. W. 2009, ApJ, 701, 1209
Brosius, J. W., & Daw, A. N. 2015, ApJ, 810, 45
Brosius, J. W., Daw, A. N., & Inglis, A. R. 2016, ApJ, 830, 101
Brosius, J. W., & Holman, G. D. 2007, ApJL, 659, L73
Brosius, J. W., & Holman, G. D. 2010, ApJL, 720, 1472
Brosius, J. W., & Phillips, K. J. H. 2004, ApJ, 613, 580
Brosius, J. W., & Phillips, K. J. H. 2004, ApJL, 613, 580
Brown, J. C. 1971, SoPh, 18, 480
Carmichael, H. 1964, NASSP, 50, 451
Chen, F., & Ding, M. D. 2010, ApJ, 724, 640
Cheng, C.-C., Feldman, U., & Doschek, G. A. 1979, ApJ, 233, 736
Cheng, X., & Ding, M. D. 2016a, ApJS, 225, 16
Cheng, X., & Ding, M. D. 2016b, ApJL, 823, L4
Cheng, X., Ding, M. D., & Fang, C. 2015, ApJ, 804, 82
Czaykowska, A., De Pontieu, B., Alexander, D., & Rank, G. 1999, ApJL, 521, L75
De Pontieu, B., Title, A. M., Lemen, J. R., et al. 2014, SoPh, 289, 2733
Tian, H., Li, G., Reeves, K. E., et al. 2014, ApJL, 797, L14
Tian, H., Young, P. R., Reeves, K. K., et al. 2015, ApJ, 811, 139
Tian, H., Young, P. R., Reeves, K. K., et al. 2016, ApJL, 823, L16
Veronig, A. M., Rybák, J., Gömöry, P., et al. 2010, ApJ, 719, 655
White, S. M., Krucker, S., Shibasaki, K., et al. 2003, ApJL, 595, L111
Woods, M. M., Harra, L. K., Matthews, S. A., et al. 2017, SoPh, 292, 38
Yan, X. L., Jiang, C. W., Xue, Z. K., et al. 2017, ApJ, 845, 18

Young, P. R., Tian, H., & Jaeggli, S. 2015, ApJ, 799, 218
Zarro, D. M., & Lemen, J. R. 1988, ApJ, 329, 456
Zhang, Q. M., & Ji, H. S. 2013, A&A, 557, L5
Zhang, Q. M., Li, D., & Ning, Z. J. 2016a, ApJ, 832, 65
Zhang, Q. M., Li, D., Ning, Z. J., et al. 2016b, ApJ, 827, 27
Zhang, Q. M., Su, Y. N., & Ji, H. S. 2017, A&A, 598, A3
Zhou, G. P., Zhang, J., & Wang, J. X. 2016, ApJL, 823, L19