Explosive Chromospheric Evaporation Driven by Nonthermal Electrons around One Footpoint of a Solar Flare Loop

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Abstract

We explore the temporal relationship between microwave/hard X-ray (HXR) emission and Doppler velocity during the impulsive phase of a solar flare on 2014 October 27 (SOL2014-10-27) that displays a pulse on the light curves in the microwave (34 GHz) and HXR (25–50 keV) bands before the flare maximum. Imaging observation shows that this pulse mainly comes from one footpoint of a solar flare loop. The slit of the Interface Region Imaging Spectrograph (IRIS) stays at this footpoint during this solar flare. The Doppler velocities of Fe XXI 1354.09 Å and Si IV 1402.77 Å are extracted from the Gaussian fitting method. We find that the hot line of Fe XXI 1354.09 Å (log T ∼ 7.05) in the corona exhibits blueshift, while the cool line of Si IV 1402.77 Å (log T ∼ 4.8) in the transition region exhibits redshift, indicating explosive chromospheric evaporation. Evaporative upflows along the flare loop are also observed in the AIA 131 Å image. To our knowledge, this is the ﬁrst report of chromospheric evaporation evidence from both spectral and imaging observations in the same flare. Both microwave and HXR pulses are well correlated with the Doppler velocities, suggesting that the chromospheric evaporation is driven by nonthermal electrons around this footpoint of a solar flare loop.

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

1. Introduction

In a typical solar flare, the released energy is about $10^{30}$ erg within dozens of minutes. Such huge energy is thought to be transferred from the magnetic energy via reconnection, which is thought to heat the plasma and to accelerate the bi-directional nonthermal electrons through the solar chromosphere, transition region, and corona. This is well known as the standard solar flare model. These accelerated electrons are guided by the newly reconnected magnetic field lines. Some of the accelerated electrons travel up to interplanetary space, and the others propagate downward to the lower corona and upper chromosphere, where they lose their energies through Coulomb collisions with the denser plasma. Subsequently, two footpoint sources are often produced along the flare loop legs in the hard X-ray (HXR) and microwave bands (Brown 1971; Asai et al. 2006), and the double ribbons are brightened in Hα, ultraviolet (UV), and extreme-ultraviolet (EUV) wavelengths (Czaykowska et al. 1999; Del Zanna et al. 2006; Milligan 2015). Meanwhile, the local chromospheric material is rapidly heated up to ∼10 MK (Antonucci et al. 1982), resulting in a higher pressure, which drives the chromospheric material upward into the corona along the solar flare loops. Thus, the hot plasma ﬁlls the solar flare loops in a process called “chromospheric evaporation” (Brown 1973; Fisher et al. 1985a, 1985b; Liu et al. 2006; Ning & Cao 2010; Brosius & Daw 2015; Tian et al. 2015; Young et al. 2015; Zhang et al. 2016; Lee et al. 2017). At the same time, the overpressure also drives the denser plasma downward into the lower chromosphere in a process called “chromospheric condensation” (Fisher et al. 1985a, 1985b; Teriaca et al. 2006; Li et al. 2015).

Chromospheric evaporation is observed in multiple wavelengths, i.e., the HXR, EUV/UV, and microwave bands. Imaging observations show that the HXR emission tends to rise with the double footpoint sources along the loop legs, eventually merging them into a single source at the loop top (e.g., Liu et al. 2006; Ning & Cao 2010; Ning 2011; Nitta et al. 2012). This process is thought to be the HXR signature of chromospheric evaporation. On the other hand, the heated materials rise upward to the corona and disturb the local plasma. This process causes the microwave emission to suddenly be cut off on the dynamic spectra. Observationally, a high-frequency cutoff drifting to low frequency is the radio signature of chromospheric evaporation (Aschwanden & Benz 1995; Karlicky 1998; Ning et al. 2009). Joint observations from spectra and images show that the blueshift of hot lines in corona tends to appear at the outside of a flare ribbon (Czaykowska et al. 1999; Li & Ding 2004; Li et al. 2015).

Chromospheric evaporation is divided into two types, i.e., “explosive” and “gentle.” Explosive evaporation takes place if the input energy ﬂux exceeds a critical value of $\sim 10^{10}$ erg cm$^{-2}$ s$^{-1}$ (Fisher et al. 1985a, 1985b). In spectroscopic observations, explosive evaporation is usually accompanied by blueshift with high speed ($\sim 100–400$ km s$^{-1}$) in the hot lines from corona, and by redshift with low speed ($\sim 10–40$ km s$^{-1}$) in the cool lines from the upper chromosphere and the transition region (Feldman et al. 1980; Ding et al. 1996; Del Zanna et al. 2006; Teriaca et al. 2006; Milligan & Dennis 2009; Chen & Ding 2010; Veronig et al. 2010; Brosius 2013; Doschek et al. 2013; Tian et al. 2014; Brosius & Daw 2015; Brosius et al. 2016; Zhang et al. 2016). Observationally, the speed of blueshift is an order of magnitude larger than that of redshift, which is due to the fact that the density of the overlying corona is less than that of the underlying lower chromosphere (Fisher et al. 1985a, 1985b; Milligan & Dennis 2009; Doschek et al. 2013). Gentle evaporation occurs when the input energy ﬂux is smaller than the critical value, and all the emission lines display blueshift
from the chromosphere through the transition region to the corona (Milligan et al. 2006; Brosius 2009; Li & Ding 2011).

In the literature, there are three mechanisms that drive chromospheric evaporation. The first one is electron-driven, which emphasizes that the nonthermal electrons accelerated by magnetic reconnection play an important role in driving chromospheric evaporation (Fisher et al. 1985b; Brosius 2003; Milligan & Dennis 2009; Tian et al. 2014, 2015; Li et al. 2015; Zhang et al. 2016). The second one focuses on the thermal energy (Fisher et al. 1985a; Falewicz et al. 2009), while the third one is driven by the energy deposition through Alfvén waves (Reep & Russell 2016). The correlation between Fe XXI13540.9 Å Doppler velocity and HXR emission from the whole flare region has already been documented in the literature (Li et al. 2015; Tian et al. 2015; Lee et al. 2017). In this paper, using observations from the Interface Region Imaging Spectrograph (IRIS, De Pontieu et al. 2014), the Nobeyama Radioheliograph (NoRH; Hanaoka et al. 1994), the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI, Lin et al. 2002), the Atmospheric Imaging Assembly (AIA, Lemen et al. 2012), and the Helioseismic and Magnetic Imager (HMI; Schou et al. 2012) on board the Solar Dynamics Observatory (SDO), we study the temporal relationship between the microwave/HXR

**Figure 1.** SXR light curves of the 2014 October 27 flare from 00:06 UT to 00:40 UT in 1.0–8.0 Å (black) and 0.5–4.0 Å (turquoise). The normalized flux is in microwaves of 34 GHz (purple) and HXR of 25–50 keV (orange) for the whole flare region for the same time intervals.

**Figure 2.** Multi-wavelength images with a FOV of 90″ × 90″ on the 2014 October 27 flare. The purple contours are from the microwaves of 34 GHz, and the white boxes indicate the sources of two footpoints. The green contours represent the AIA 1600 Å intensities at the scale of 200 DN s⁻¹. The red dashed lines in AIA 131 Å outline the possible flare loops. The long blue line represents the slit of IRIS and the short blue line marks the region studied here.
emission and the Doppler velocity of the SOL2014-10-27 event to prove that nonthermal electrons drive chromospheric evaporation around one footpoint of a solar flare loop.

2. Data Analysis and Results

The studied event takes place in NOAA AR12192 on 2014 October 27. It is an M7.1 flare in the GOES light curve. It displays typical features of solar flares, such as two footpoint sources in microwave and HXR images. The slit of IRIS stays at one footpoint during the impulsive phase of the solar flare, which gives us a good chance to study the temporal evolution of the Doppler velocity in coronal and transition region lines, i.e., FeXXI 1354.09 Å and SiIV 1402.77 Å. Figure 1 shows the GOES SXR fluxes in 1.0–8.0 Å (black) and 0.5–4.0 Å (turquoise), respectively. The event starts at around 00:06 UT, and peaks at about 00:34 UT from GOES SXR light curves. Meanwhile, the microwave 34 GHz (purple) and HXR 25–50 keV (orange) emissions display a series of regular and periodic peaks during the impulsive phase of this solar flare, which result in several nonthermal pulses (e.g., Li et al. 2017), as marked by the Roman Capitals “I,” “II.” The first pulse (“I”) is studied in this paper.

Figure 2 shows multi-wavelength images from several instruments during the first pulse. They have the same field-of-view of 90′ × 90′. Panel (a) displays the integral intensity image (~2″/45/pixel) in microwaves of 34 GHz from 00:09 UT to 00:10 UT. The double footpoint sources are marked by the white boxes. Among them, one is bright (ft1), while the other one is faint (ft2). This is confirmed by a RHESSI CLEAN image (~2″/pixel) at 25–50 keV, as shown in panel (b). The contour of ft2 is from the microwave emission. Panel (c) gives the line-of-sight (LOS) magnetogram (~0″6/pixel) overlaid with the AIA 1600 Å contours. The bottom panels show the EUV/UV snapshots in SDO/AIA 131 Å and 1600 Å (~0″6/pixel), and IRIS/SJI 1330 Å.
The AIA 1600 Å image is applied to co-align with the SJI 1330 Å image (Cheng et al. 2015; Li et al. 2015; Tian et al. 2015) because they both contain continuum emission around the temperature minimum, which is dominant in many bright features. The flare ribbons in AIA 1600 Å and SJI 1330 Å are connected by the hot loops in AIA 131 Å, as indicated by the dashed lines. Consistent with the standard solar flare model, panel (e) shows that the double footpoint sources overlap on the two flare ribbons. The slit of IRIS crosses one flare ribbon and fixes on the edge of one footpoint (ft1), as shown by the long blue line along the 45° to the north–south direction.

The hot line of Fe xxi 1354.09 Å (log $T \sim 7.05$, De Pontieu et al. 2014) in the corona and the cool line of Si iv 1402.77 Å (log $T \sim 4.8$, De Pontieu et al. 2014) in the transition region are widely used to investigate chromospheric evaporation (Tian et al. 2014, 2015; Li et al. 2016; Zhang et al. 2016). Figure 3 shows the IRIS observation at spectral windows of “Fe xxi” (a), (c), (e) and “Si iv” (b), (d), (f) at three instances. The Y-axis is along the slit direction. They have been pre-processed with the routines of “iris_orbital_corr_j2.pro” (Tian et al. 2014; Cheng et al. 2015) and “iris_prep_despike.pro” (De Pontieu et al. 2014) in Solar Soft Ware. The absolute wavelength calibration is also manually performed with relatively strong neutral lines, i.e., “O i” 1355.5977 Å and “S i” 1401.5136 Å (e.g., Tian et al. 2015). The overplotted black profile shows the spectrum at the position of about 38″6, which is marked by the short purple line on the left side. This position is located at the edge of a flare ribbon in the northwest labeled with the short blue line in Figure 2(e). The multi-Gaussian functions (purple profile) superimposed on a linear background (green line) are used to fit the IRIS spectrum at the “Fe xxi” window to extract the flare line of Fe xxi 1354.09 Å. The emission lines that are blended with the broad line of Fe xxi 1354.09 Å should be excluded, i.e., 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 some unidentified lines at 1353.32 Å and 1353.39 Å (Polito et al. 2015; Tian et al. 2015; Young et al. 2015). Here, we fixed these blended line positions, constrained their widths, and tied their intensities to the lines in other spectral windows (e.g., Li et al. 2015, 2016). Finally, we can obtain the line profile of Fe xxi 1354.09 Å, as shown by the turquoise line. The transition region line of Si iv 1402.77 Å is fitted with a single-Gaussian function (purple profile) with a linear background (green line). Both the Doppler velocities of Fe xxi 1354.09 Å and Si iv 1402.77 Å are detected by the fitting line centers subtracting the referenced line centers (Li et al. 2014; Tian et al. 2015).

To study the relationship between the microwave/HXR emission and the evaporation speed, Figure 4(a) shows the normalized flux in microwave (black) and HXR (green) bands, and the temporal evolution of the Doppler velocity in
Fe XXI 1354.09 Å (blue) and Si IV 1402.77 Å (red) on the slit position of 38.76 (short purple line in Figure 3). The hot line of Fe XXI 1354.09 Å in the corona displays blueshift, while the cool line of Si IV 1402.77 Å in the transition region exhibits redshift, which indicates the explosive chromospheric evaporation around the footpoint of ft1. The maximum velocities of the blueshifts and redshifts are about −67 km s\(^{-1}\) and 36 km s\(^{-1}\) during the first pulse between 00:08 and 00:11 UT. The microwave light curves are solid (black) at ft1 and dashed (black) at ft2. They are integrated over the regions in the white boxes in Figure 2(a), respectively. The observations show that the pulse (between 00:08 and 00:11 UT) studied here completely arises from ft1, and the microwave emission at ft2 is monotonously increasing. However, the HXR flux is integrated over the whole flare region, which is the same as that in Figure 1. These light curves are well correlated during the pulse interval, but their different time cadences make it impossible for the points to correspond one-to-one. NoRH, RHESSI, and IRIS have cadences of 1, 4, and 16.2 s, respectively. In this paper, we use all nine points from the Doppler velocity around the pulse (between 00:08:30 UT and 00:11:00 UT), and their nearby points of microwave and HXR emissions. Thus, nine points are extracted from all the light curves, as marked by the purple symbols (“+” or “x”).

Figure 4(b) shows the dependence of the Doppler velocities of Fe XXI 1354.09 Å (“+”) and Si IV 1402.77 Å (“x”) on microwave 34 GHz (black) and HXR 25–50 keV (purple) emissions during the pulse interval, i.e., between 00:08:30 UT and 00:11:00 UT. As expected from the model of electron-driven chromospheric evaporation, we find a negative correlation (−0.96/−0.87) between the microwave/HXR emission and the Doppler velocity of the hot line (Fe XXI 1354.09 Å at ft1 (“−”) indicates that the Doppler velocity of Fe XXI 1354.09 Å is blueshift), and a positive correlation (+0.91/+0.82) between the microwave/HXR emission and the Doppler velocity of cool line (Si IV 1402.77 Å, “+” indicates that the Doppler velocity of Si IV 1402.77 Å is redshift). Such high-correlation coefficients suggest that the nonthermal electrons that are accelerated by the magnetic reconnection drive the explosive chromospheric evaporation around the footpoint of ft1.

Based on the chromospheric evaporation process, the plasma upflows are expected to be observed along the flaring loops. Figure 2(d) shows that the loops (red dashed lines) in AIA 131 Å connect the double ribbons in AIA 1600 Å. These loops become brighter and brighter with the flare development. Meanwhile, these loops expand with time. Figure 5(a) shows the time difference image in AIA 131 Å between the pulse maximum (~00:09:32 UT) and the flare beginning (~00:06:08 UT). The two purple lines outline the expansion loop that covers the hot plasma upflows due to chromospheric evaporation. Figure 5(b) gives its time–distance image, and the Y-axis from bottom to top corresponds to the loop from ft2 to ft1. Thus, the loop top is near the middle position in the Y-axis, i.e., ~41roots2. It clearly shows the evaporation upflows from double footpoints through the legs to the loop top, as indicated by the purple arrows during 00:08:30–00:12:00 UT, which is consistent with the microwave and HXR pulses (“I”). The evaporation speeds are estimated to be ~112 km s\(^{-1}\) and ~99 km s\(^{-1}\) without considering the projection effect.

3. Conclusions and Discussions

Based on observations from IRIS, NoRH, and RHESSI, we explore the temporal relationship between the Doppler velocity of Fe XXI 1354.09 Å and Si IV 1402.77 Å lines and microwave/HXR emission in microwave 34 GHz and HXR 25–50 keV wavelengths during the pulse of a solar flare on 2014 October 27. The completely new observational result is that the explosive chromospheric evaporation driven by nonthermal electrons originates from one footpoint of a solar flare loop. Meanwhile, the evaporation upflows are also observed from the double footpoints to the loop top, in a AIA 131 Å image. This is consistent with the standard solar flare model. Our results agree well with previous findings about the temporal correlation between the Doppler velocity and HXR flux, which represents the deposition rate (Li et al. 2015; Tian et al. 2015; Lee et al. 2017), and are also consistent with studies of the spatial correlation between the upflows/downflows and HXR sources in solar flares (Brosius & Holman 2009; Milligan & Dennis 2009; Veronig et al. 2010; Brosius et al. 2016; Zhang et al. 2016). It has recently been demonstrated that explosive evaporation can also be driven by dissipation through Alfvén waves, and this mechanism can produce HXR bursts (Reep & Russell 2016). Therefore, only the presence of an HXR burst is impossible to rule out for the contribution from the heating of Alfvén waves. On the other hand, a microwave pulse is observed around the peak time of the IRIS Doppler velocity at one footpoint of a solar flare loop.
implying that nonthermal electrons are injected into the chromosphere along the flare loop in the Sun. Thus, the observations in this case suggest an electron-driven chromospheric evaporation.

Figures 2(e) and (f) show that the slit of IRIS crosses one of the flare ribbons. The studied position of the Doppler velocity is just at the edge of the flare ribbon, indicating that explosive chromospheric evaporation appears at the outside of the flare ribbon, which is consistent with previous findings (Czaykowska et al. 1999; Li & Ding 2004; Li et al. 2015; Tian et al. 2015). On the other hand, Figure 2(a) exhibits that the slit of IRIS does not appear in the footpoint center, which may be due to the lower spatial resolution of the microwave image (~4")9). Future work will require higher-resolution observations in the microwave or HXR bands, including time and spatial resolutions.

In this Letter, only the first pulse (“I”) in the microwave and HXR emissions is used to investigate the explosive chromospheric evaporation. We did not find any correspondence between the microwave (or HXR) emission and Doppler velocity during the other pulses, i.e., the second microwave pulse at about 00:13 UT (“II”). This may be because the upflows/downflows of the other microwave pulses are very complex. The upflows are from the new heated plasma, which moves upward along the loop, while the downflows from the last evaporated material may eventually cool and precipitate back down along the loop (e.g., Brosius 2003; Milligan & Dennis 2009). It could also be because the location of energy deposition is not covered by the slit of IRIS. The good correlation between Doppler velocity and microwave/HXR emission may be found when shifting the slit position (e.g., Li et al. 2015).

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