



IRIS, *Hinode*, *SDO*, and *RHESSI* Observations of a White Light Flare Produced Directly by Non-thermal Electrons

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Abstract

An X1.6 flare occurred in active region AR 12192 on 2014 October 22 at 14:02 UT and was observed by *Hinode*, *IRIS*, *SDO*, and *RHESSI*. We analyze a bright kernel that produces a white light (WL) flare with continuum enhancement and a hard X-ray (HXR) peak. Taking advantage of the spectroscopic observations of *IRIS* and *Hinode*/EIS, we measure the temporal variation of the plasma properties in the bright kernel in the chromosphere and corona. We find that explosive evaporation was observed when the WL emission occurred, even though the intensity enhancement in hotter lines is quite weak. The temporal correlation of the WL emission, HXR peak, and evaporation flows indicates that the WL emission was produced by accelerated electrons. To understand the WL emission process, we calculated the energy flux deposited by non-thermal electrons (observed by *RHESSI*) and compared it to the dissipated energy estimated from a chromospheric line (Mg II triplet) observed by *IRIS*. The deposited energy flux from the non-thermal electrons is about $(3\text{--}7.7) \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$ for a given low-energy cutoff of 30–40 keV, assuming the thick-target model. The energy flux estimated from the changes in temperature in the chromosphere measured using the Mg II subordinate line is about $(4.6\text{--}6.7) \times 10^9 \text{ erg cm}^{-2} \text{ s}^{-1}$: $\sim 6\%\text{--}22\%$ of the deposited energy. This comparison of estimated energy fluxes implies that the continuum enhancement was directly produced by the non-thermal electrons.

Key words: Sun: activity – Sun: chromosphere – Sun: corona – Sun: flares – Sun: UV radiation – techniques: spectroscopic

1. Introduction

Solar flares are one of the most energetic energy release processes in the heliosphere. When a flare occurs we can observe the multi-wavelength response from microwaves to X-rays such as radio bursts in the impulsive phase, H α emission along the flare ribbons, soft X-ray emission in the post-flare loop arcade, and hard X-ray (HXR) emission at the footpoints and looptop region (Fletcher et al. 2011).

Several models of solar flares have been proposed on the basis of these multi-wavelength observations. The standard model of a solar flare (CSHKP; Carmichael 1964; Sturrock 1968; Hirayama 1974; Kopp & Pneuman 1976) proposes that magnetic reconnection occurs at coronal heights and the magnetic energy released is transported to the lower atmospheric layers (e.g., the chromosphere) by thermal conduction (Nagai 1980; Yokoyama & Shibata 2001), non-thermal particles (Nagai & Emslie 1984; Fisher et al. 1985a, 1985b, 1985c), or the Poynting flux of an Alfvén wave (Fletcher & Hudson 2008). The transferred energy heats the plasma and generates overpressure in the lower atmosphere. Dense plasma is then evaporated toward the corona along the magnetic field (chromospheric evaporation) and we then observe post-flare loops emitting in the EUV and soft X-rays.

Sometimes strong flares produce continuum enhancements as a photospheric response during the impulsive phase of the flare, and this is termed a white light flare (WLF) (Carrington 1859; Švestka 1966). Previous observations in visible

wavelengths and HXRs showed that the continuum enhancement in WLFs is well correlated with HXR emission both spatially and temporally (Neidig 1989; Hudson et al. 1992; Metcalf et al. 2003; Watanabe et al. 2010a; Krucker et al. 2015; Kuhar et al. 2016). As a result of this correlation, it has been thought that WLFs are produced by the energy transported from accelerated particles such as non-thermal electrons (Brown 1971; Hudson 1972).

With recent observations at high spatial resolution, white light (WL) emission has been reported even in C-class flares (Matthews et al. 2003; Hudson et al. 2006). The electron flux from these low-energy events is not enough to penetrate and heat the photosphere directly. Therefore, other heating mechanisms have also been considered. For example, Zirin & Neidig (1981) proposed that high-energy protons carry the energy, and Machado et al. (1989) suggested that WL emission is produced by electrons that heat the chromosphere directly and the photosphere indirectly through radiative backwarming. However, the true heating mechanism in the lower atmosphere remains unclear. We believe that understanding the flare dynamics during the impulsive phase, and the lower atmospheric response to the flare, are key to clarifying the heating and energy transport processes.

Previous observational studies of chromospheric evaporation have revealed strong blueshifted emission ($>100 \text{ km s}^{-1}$) in coronal lines (Antonucci et al. 1982; Brosius 2003, 2009, 2013a, 2013b; Milligan & Dennis 2009) and red asymmetries ($40\text{--}100 \text{ km s}^{-1}$) in chromospheric lines (Ichimoto & Kurokawa 1984; Kamio et al. 2005; del Zanna et al. 2006). Some flares also show a redshift in coronal lines formed around a few MK (Imada

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et al. 2008; Milligan & Dennis 2009; Watanabe et al. 2010b), and direct imaging observations of chromospheric evaporation upflows have been observed by *Hinode*/XRT (Nitta et al. 2012). Hydrodynamic simulations can reproduce aspects of the observations and predict two different types of evaporation flows depending on the deposited energy flux: “explosive” and “gentle” evaporation (Fisher et al. 1985a, 1985b, 1985c).

Recently, the *Hinode*/EUV Imaging Spectrometer (EIS, Culhane et al. 2007) and *Interface Region Imaging Spectrograph* (IRIS, De Pontieu et al. 2014) have provided us with spectroscopic observations at high spatial and temporal resolution in the EUV/UV (Li & Ding 2011; Graham & Cauzzi 2015; Tian et al. 2015). The combined power of the instruments allows us to investigate flare properties and dynamics through the entire atmosphere from chromosphere to corona (Li et al. 2015b; Polito et al. 2015, 2016).

Most relevant to this work are several studies comparing the deposited flare energy with observed continuum enhancements. For example, Watanabe et al. (2010a) found that the energy of the WL emission observed by *Hinode*/Solar Optical Telescope (SOT) was equivalent to the energy supplied by all the electrons accelerated to above 40 keV, which suggests that highly accelerated electrons are responsible for producing WL emission. Recently, Kleint et al. (2016) investigated the radiated energy from the continuum enhancement observed from the UV to IR during a flare using *IRIS*, *Solar Dynamics Observatory* (SDO), and the Facility Infrared Spectrometer (FIRS), and also found that the deposited energy was sufficient to produce the UV and visible continuum emission in the flare.

In this study, we describe the temporal evolution of the spectral properties and quantitatively estimate the energy flux of an X1.6 flare using combined observations from *IRIS*, EIS, *RHESSI* (Lin et al. 2002), and *SDO*. The whole flare evolution, from the beginning of the impulsive phase to the gradual phase, is captured by these instruments simultaneously, and the strong flare produces WL emission. Previously, Li et al. (2015a), Thalmann et al. (2015), and Veronig & Polanec (2015) also investigated this well observed flare using *SDO*, *RHESSI* and *IRIS*. Thalmann et al. (2015) and Veronig & Polanec (2015) mainly focused on the magnetic reconnection rates and the *RHESSI* HXR profiles of this flare, and Li et al. (2015a) investigated the relationship between Doppler velocity patterns derived from *IRIS* Fe XXI and C I and the *RHESSI* HXR intensity. Those studies showed that the flare energy is injected into high-energy electrons, and that they could drive the evaporation flow in the flare. We present the flare observations from each instrument in Section 2, and the temporal evolution of the spectral properties (intensity, Doppler velocity, line width, density, and temperature) of the flare kernel during the impulsive phase with the other continuum and X-ray observations in Section 3. We discuss the comparison between the deposited energy from the non-thermal electrons and the observed spectroscopic properties in Section 4. A summary of our results is given in Section 5.

2. Observations and Data Analysis

2.1. X1.6 Flare in AR 12192

We investigate an X1.6 flare which occurred on 2014 October 22 in active region AR 12192. AR 12192 was the largest active region in this solar cycle and it produced six X-class flares and 31 M-class flares. Figure 1 shows the *GOES*

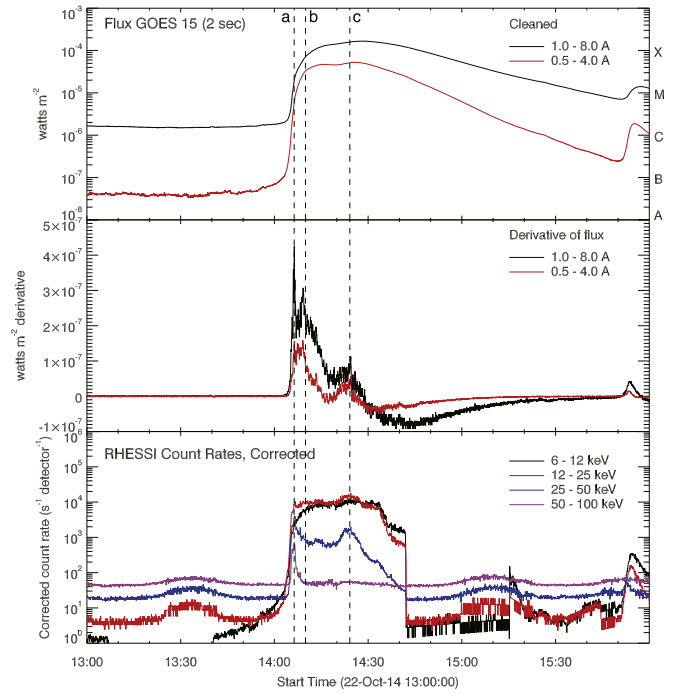


Figure 1. *GOES* X-ray light curve (top) of the X1.6 flare on 2014 October 22 14:06 UT and its time derivative (middle). The *RHESSI* count rates for the different energy bands are plotted in the bottom panel. The vertical dashed lines (a–c) mark the times of the three peaks in the time derivative of the *GOES* X-ray light curve.

soft X-ray (0.5–4 Å and 1–8 Å) light curve, its time derivative, and the *RHESSI* hard and soft X-ray light curves of the flare event. The flare started at about 14:02 UT and peaked at 14:28 UT. The gradual phase of the flare emission declined until an M-class flare occurred at 15:54 UT. The vertical dashed lines mark the specific times at which we present the spectral properties of the flare: (a: the beginning of the impulsive phase (14:06 UT), b: the rise phase (14:09 UT), and c: the peak (14:24 UT); see Section 3). Positions a, b, and c also mark the peaks of the time derivative of the soft X-ray (SXR) curve, which correspond to the HXR peaks (bottom), as expected from the Neupert effect (Neupert 1968).

Figure 2 shows context images of the flare obtained by *SDO*/Atmospheric Imaging Assembly (AIA, Lemen et al. 2012) in the 211 Å (a–c) and 1700 Å (e–g) channels, and *IRIS* C II 1330 Å slit jaw images (SJIs) overlaid with EIS 195 Å contours (panels i–k) for different timings, before the flare (~13:34 UT), the first HXR peak (~14:06 UT), and the SXR peak (~14:24 UT). Panels (d) and (h) display the *SDO*/Helioseismic and Magnetic Imager (HMI, Schou et al. 2012) continuum and a running difference image at the time the WLF occurred, respectively. Panel (l) shows the polarity inversion line from the HMI magnetogram contoured on an *IRIS* SJI to show the magnetic field configuration.

When we look at the continuum and lower atmospheric (AIA 1700 Å) images, we can see that the flare occurred at the boundary of the large umbra and the satellite penumbra. When the first HXR peak of the flare was observed (around 14:06 UT), we can see continuum enhancements (the WLF) at two bright kernels (panel (h)), which correspond to the footpoints of the flare loop structure (panel (c)). Then, two ribbons extend in the east–west direction (panels (g) and (k)). Before the flare, around 13:34 UT (panels (a), (e), and (i)), we can see a small

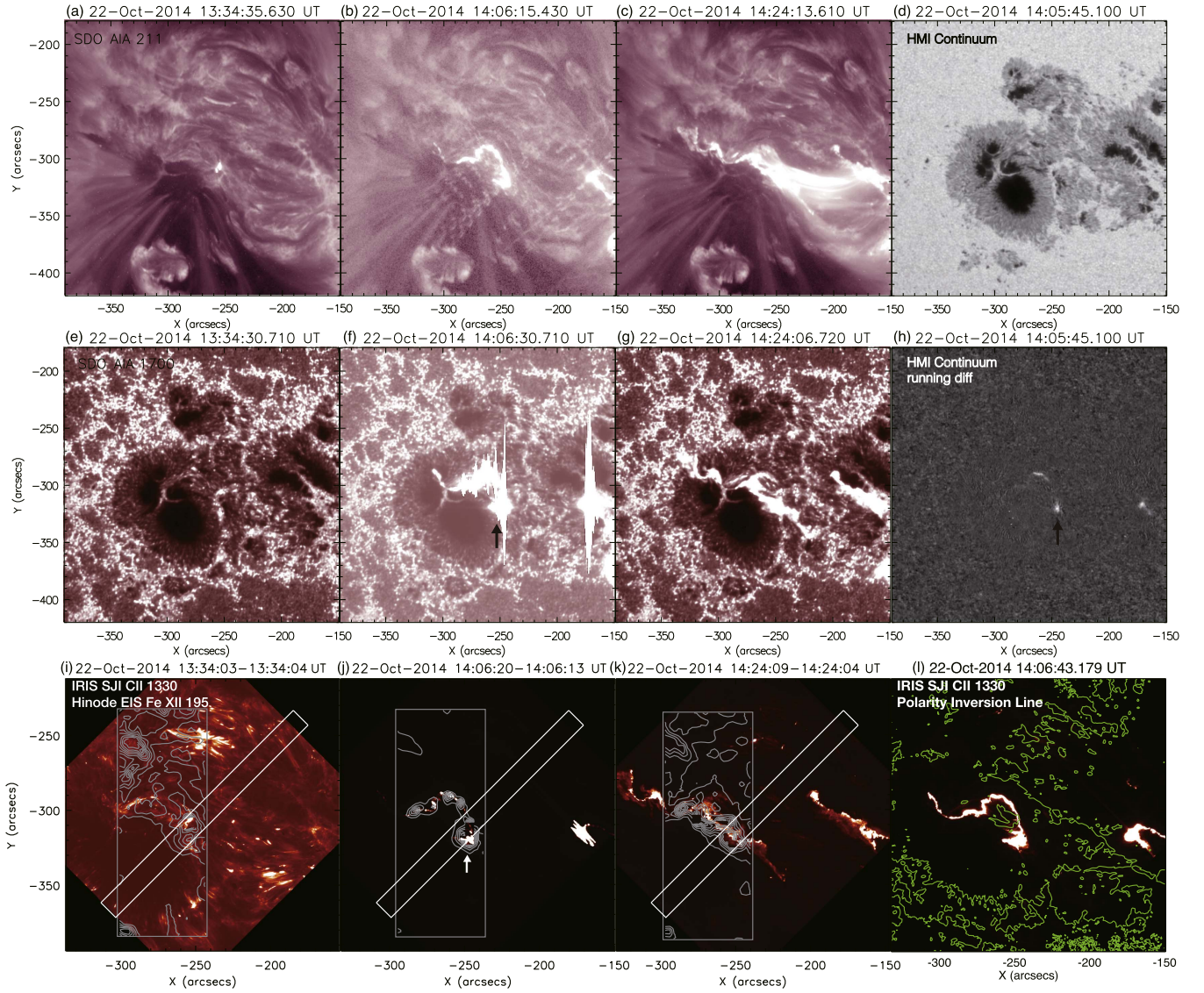


Figure 2. Context *SDO* and *IRIS*/SJI C II 1330 Å images for the X1.6-class flare on 2014 October 22. (a)–(c): AIA 211 Å, (e)–(g): AIA 1700 Å channel images; (i)–(k): *IRIS* SJI C II 1330 Å slit jaw images overlaid with EIS 195 Å intensity contours (gray line) taken before the flare ($\sim 13:37$ UT), at the time of the first HXR peak ($\sim 14:06$ UT), and at the flare peak ($\sim 14:24$ UT). The white dashed box in the *IRIS* SJI corresponds to the location of the *IRIS* raster. Panels (d) and (h) display the *SDO*/HMI continuum and a running difference image at 14:05:45 UT, respectively. Panel (l) depicts the polarity inversion line from the HMI magnetogram on the *IRIS* SJI around timing (a) in Figure 1. The bright kernel we analyzed is marked with an arrow.

brightening near the east side of the flare kernel. This kernel was observed simultaneously in the *IRIS* and EIS scanning rasters. We analyzed the evolution of the plasma properties of this bright kernel and estimated the energy flux.

2.2. Spectroscopic Observations from *Hinode*/EIS and *IRIS*

EIS captured the flare with the study “HH_Flare_raster_v6,” which ran from 13:01:56 UT to 15:56:56 UT. This EIS study is designed for observing flares using a moderate-cadence raster scan. The 2'' slit scans 20 positions with coarse 3'' steps between them, and the field of view is $59'' \times 152''$. The exposure time at each position is 9 s and the raster scan takes about 3.5 minutes. The study has 12 spectral windows and we used 10 spectral lines covering the temperature range from $\log(T/\text{K}) = 4.9\text{--}7.2$. These are listed in Table 1. The spectral resolution of the EIS is about 0.022 Å.

At the same time, *IRIS* was running a very large, coarse, eight-step raster. It uses the $0''.33 \times 175''$ slit with 2'' steps and

so covers a field of view of about $14'' \times 175''$ in around 130 s. The exposure time at each position is 16 s. The spectral and spatial resolutions of *IRIS* are 0.025 Å and $0''.32$, respectively. The *IRIS* slit direction was rotated 45° relative to its center for this observation. The observing program includes nine spectral windows in the FUV (1332–1358 Å and 1389–1407 Å) and NUV (2783–2834 Å). In this study, we only analyze the spectral lines that are close to optically thin, O I, Si IV, and Fe XXI, for measuring the Doppler velocity, and we used the O IV and Mg II lines for investigating the chromospheric response. The spectral lines we used are summarized in Table 1.

To obtain the intensity, Doppler velocity, and line width as functions of time, we fitted the spectral lines in Table 1 using single and multiple Gaussians. Figures 3 and 4 show examples of the line profiles from EIS and *IRIS*, respectively. In Figure 3, the green solid line is the fitted spectrum and the red dashed lines indicate each component of the multiple Gaussian fitting.

Table 1
List of the Spectral Lines Used in the Present Study

Instrument	Line ID (Å)	$\log(T_{\max}/K)$
EIS	He II 256.32	4.9
	O V 248.46	5.4
	Fe X 184.54	6.1
	Fe XII 195.12	6.2
	Fe XIV 264.79 *	6.3
	Fe XIV 274.20 *	6.3
	Fe XV 284.16	6.4
	Fe XVI 263.00	6.8
	Fe XXIII 263.77	7.2
	Fe XXIV 192.03	7.2
IRIS	O I 1355.6	4.5
	Si IV 1402.8	4.9
	Fe XXI 1354.1	7.1
	Mg II 2798.8	4.0
	O IV 1399.77 *	5.2
	O IV 1401.16 *	5.2

Note. The peak formation temperatures of the spectral lines are taken from the CHIANTI database version 7.0. Lines used for the density determination are marked with asterisks.

The red and green dotted vertical lines indicate the fitted line center of each spectral line component from a multiple Gaussian fitting, and the estimated velocities are written in Figure 3. To obtain a reference wavelength for the EIS spectra, we measured the average line centers before the flare (between 13:01 and 13:51 UT), and these are marked with vertical dashed lines. In Figure 4, the green solid line is the fitted spectrum and the dashed lines indicate each component of the multiple Gaussian fits. The red dashed fitted components are Fe XXI (in the upper panels) and the second component of Si IV (in the lower panels). The reference wavelengths for *IRIS* were determined by taking the difference between the theoretical wavelengths and averaged observed wavelengths of O I 1355.60 Å and Si IV 1401.51 Å before the flare. These are marked by vertical dashed lines in the figure. The theoretical wavelength of Fe XXI is taken from the CHIANTI atomic database (Dere et al. 1997; Landi et al. 2012) and is denoted by the vertical dotted-dashed line.

2.3. SDO and RHESSI Observations

We also used AIA and HMI on board *SDO* to understand the global structure and magnetic field configuration of the flare. AIA provides multiple temperature images covering $\log(T/K) = 3.7\text{--}7.2$ with a high time cadence of about 12 s and a spatial resolution of 1.2 arcsec. We used AIA 1700 Å and 211 Å filter images for context (Figure 2), and took advantage of the high temporal resolution of AIA to investigate the variations in flare intensity and compare them to what is observed by EIS and *IRIS*. The temporal variation of the intensity in different AIA filters is plotted in Figure 5. HMI provides full-Sun line-of-sight magnetograms and continuum images at a spatial resolution of $\sim 1''$ and a temporal cadence of 45 s. Using the continuum data, we confirmed that the WLF kernel is coincident with the same bright UV kernel we analyzed.

We also investigated the hard and soft X-ray emission from the flare using the *RHESSI* X-ray spectrometer. We plotted the light curve of the emission in the ranges 30–100 keV and 12–25 keV in Figure 1. To obtain images of the HXR and SXR

emission, we used the “Clean” method with 300 iterations and a temporal resolution of 2 minutes, which is similar to that of the *IRIS* raster. The left panel in Figure 6 shows an HMI intensity difference image with the cleaned *RHESSI* HXR and SXR intensity contours (50%, 60%, 70%, 80%, and 90%) overlaid.

2.4. Coalignment of SDO, Hinode/EIS, and IRIS

We coaligned the flare observations from *Hinode*, *IRIS*, *RHESSI*, and *SDO* as follows. First, we used *SDO*/AIA observations as the reference image and aligned the AIA 1600 Å image with the *IRIS* SJI 1330 Å images. The *IRIS* slit was rotated 45° from the north–south direction, so we de-rotated the SJI images and then aligned them with the AIA images. Then, we aligned the EIS Fe XII 195.12 Å raster images with AIA 193 Å filter images. For this alignment we calculated the offset values using the procedure “align_map.pro” available in the Solar Software (SSW) package. The offset values vary within $\sim 2''$, and the EIS and *IRIS* SJI images are overlaid in the bottom panels of Figure 2.

3. Results

3.1. Temporal Evolution of the Continuum, UV, and X-Ray Emission in the Bright Kernel

We found that the WLF signature of the bright kernel in the HMI images and the HXR emission observed by *RHESSI* were located at the same position (left panel in Figure 6). To check the temporal evolution we plotted the light curve of the HMI continuum intensity in the bottom panel of Figure 7, and the HXR and SXR light curves for the location of the bright kernel in the first and second rows. We also plotted the light curves for the chromospheric and flaring line intensities from *IRIS* (O I, Si IV, Fe XXI) for comparison.

First, we note that the HXR peak and enhancement of the chromospheric line intensity (O I) appear at the beginning of the flare ($\sim 14:04$ UT). Second, the continuum enhancement starts to appear around the same time and reaches its maximum within 2 minutes. Third, the SXR emission shows two broad humps, one near the HXR peak time and another, lower peak around 16 minutes later. This suggests that the heated plasma was evaporated and the increased density and temperature are observed as enhanced SXR emission. Fourth, the emission from Fe XXI increases around 14:24 UT. We note that, even though the intensity of Fe XXI is weak, emission is detected at the beginning of the flare (14:04–14:11 UT). This suggests that the enhanced Fe XXI emission might be caused by the density enhancement of the hot plasma.

3.2. Temporal Evolution of the Spectral Properties of the Bright Kernel

3.2.1. Intensity

Figures 5, 8, and 10 (upper panel) show the temporal variation of the intensities of the bright kernel at different wavelengths from *SDO*, EIS, and *IRIS*, respectively. The *SDO*/AIA intensities in Figure 5 are normalized by their maximum intensity during the period from 13:00 UT to 16:00 UT. Together EIS and *IRIS* provide the temporal variation of the intensity over a wide range of temperature from $\log(T/K) = 4.5\text{--}7.2$.

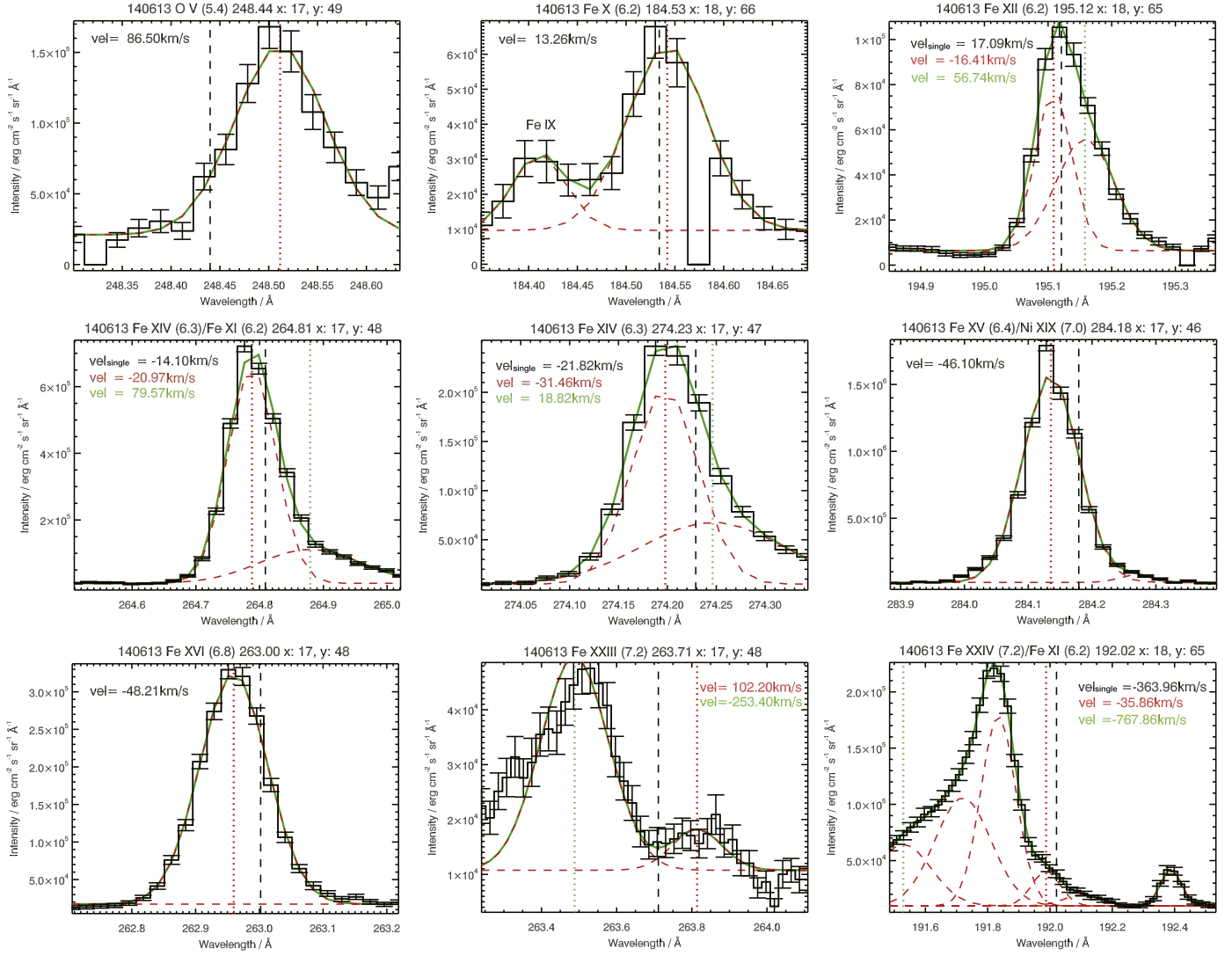


Figure 3. EIS spectral line profiles of each emission line for the bright kernel observed at 14:06:13 (impulsive phase). The green solid lines and red dashed lines represent the total line profiles from single or multiple Gaussian fits and each Gaussian component, respectively. The black vertical dashed lines represent the rest wavelengths obtained from averaging the line center before the flare from 13:01 to 13:51 UT. The red and green vertical dotted lines correspond to the line centers of the fitted line profile for the single Gaussian and the shifted component from the multiple Gaussian fit.

From the intensity variation, we can see analogous behavior in certain temperature ranges: $\log(T/K) = 4.5\text{--}5.8$ (cooler), $\log(T/K) = 5.8\text{--}6.4$ (middle), and $\log(T/K) = 6.4\text{--}7.2$ (hotter). It seems that the temperature response of the flare is similar within these temperature ranges and transitions at $\log(T/K) \sim 5.8$ and $\log(T/K) \sim 6.4$. In the cooler emission, such as $1600\text{ \AA}$ and $1700\text{ \AA}$ in Figure 5 or He II or O V in Figure 8, the response of the flare is seen as a sharp intensity enhancement when the flare starts (time a in Figure 1) with no significant enhancement during the gradual phase. It seems that the intensities peak a little later in the hotter emission lines (e.g., Fe XXIV and Fe XXIII) than in the cooler lines and there is a significant intensity enhancement during the gradual phase. In the middle temperature range, e.g., Fe X–Fe XVI in Figure 8, there are several peaks during the gradual phase. It seems that there are still bursts of intensity enhancement after the main flare, albeit not strong enough to produce WL or HXR emission.

3.2.2. Doppler Velocity

The upper panel in Figure 9 and the middle row in Figure 10 show the temporal variation of the Doppler velocity at different wavelengths. The most significant variation in velocity is seen at the impulsive phase of the flare around 14:06 UT. A strong blueshift is observed in the flaring temperature lines, Fe XV–Fe XXIV, and a redshift is observed in the chromospheric lines, O V and Si IV, which is consistent with the Doppler velocity pattern expected from explosive evaporation (Figures 3 and 9). After the impulsive phase the blueshift in the higher-temperature lines quickly changes to a weak redshift, which lasts more than an hour; essentially until the hotter emission disappears (Figure 10). A strong redshift is also seen in the cooler lines during the impulsive phase, and weak redshifted emission is observed during the gradual phase.

We plotted the velocity as a function of the line formation temperature in Figure 11. Panels (a)–(c) show the velocity pattern before the flare, during the impulsive phase, and during the gradual phase. The velocity pattern we discussed is clearly seen in the figure. Moreover, the velocity becomes larger at

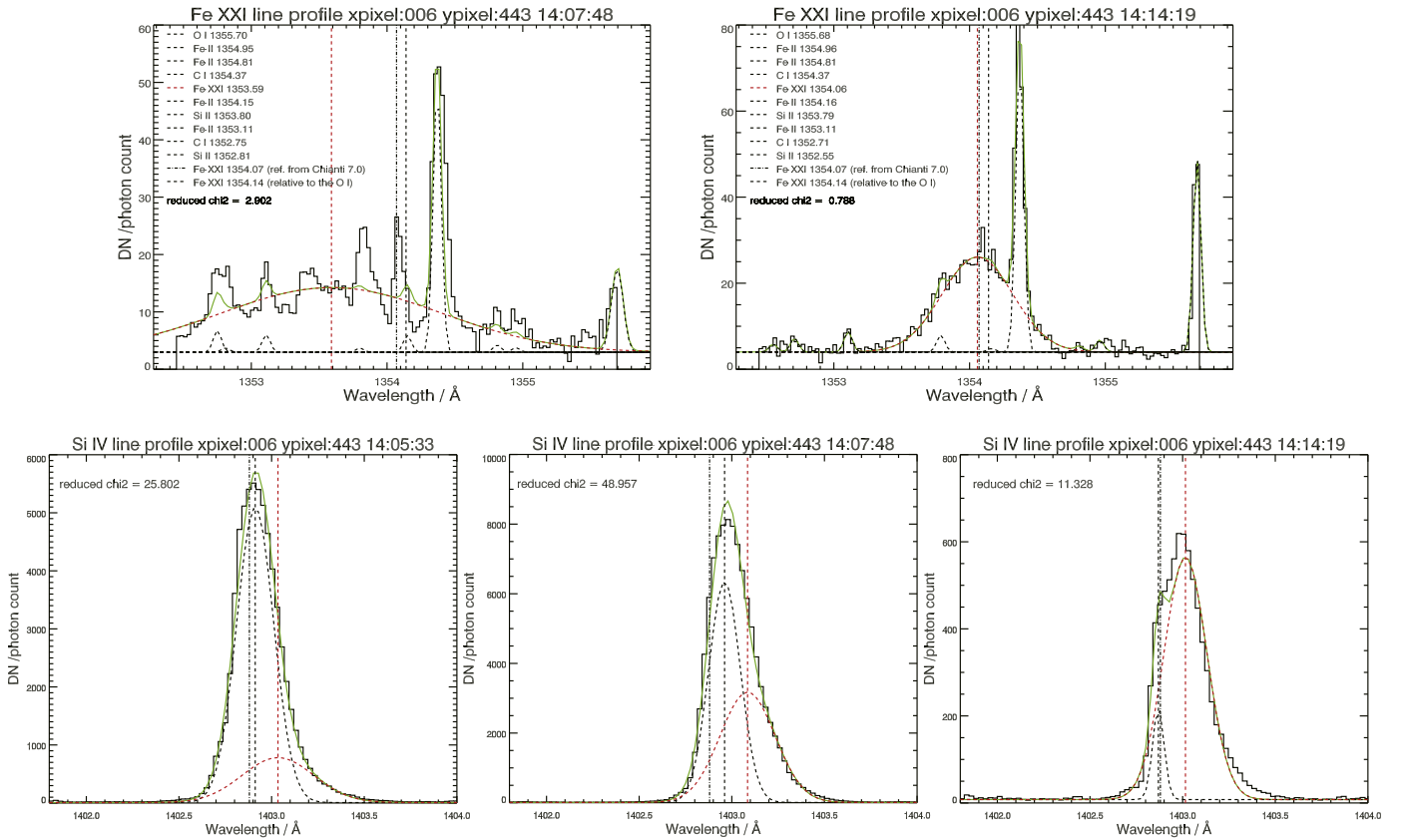


Figure 4. *IRIS* spectral line profiles of Fe XXI (top) and Si IV (bottom) for the bright kernel observed during the impulsive phase. The green solid lines and black dotted lines represent the total line profiles from multiple Gaussian fits and each Gaussian component, respectively. In the upper panels, the black vertical dashed and dotted-dashed lines represent the rest wavelengths relative to O I and the reference wavelengths from the CHIANTI atomic database, respectively. In the lower panels, the dotted-dashed and dashed lines show the rest wavelength and the first Gaussian fit component of Si IV, respectively. The red vertical dashed line corresponds to the line center of the fitted line profile for the shifted component of Fe XXI and Si IV. The Fe XXI emission and the second Gaussian fit for Si IV are marked with a red dotted Gaussian line profile.

higher temperatures, which is a similar behavior to what has been reported previously by, e.g., Milligan & Dennis (2009) and Polito et al. (2016), and is consistent with theoretical expectations (Nagai & Emslie 1984).

We note that a strong blueshift was observed only at the beginning of the flare even though the intensity enhancement in the hotter lines is quite weak. Figure 10 shows that the Fe XXI intensity from *IRIS* is weak, but the Doppler velocity shows a strong outflow at the start time of the flare ($\sim 14:06$ UT). The EIS observations also show that a strong blueshift is observed in the hotter lines even when the intensity is weak (Figures 3 and 8). So, it appears that higher-temperature emission exists and we can observe the dynamics even when there is no strong intensity signature. The intensity may be weak because the density is low in the high-temperature plasma in the early phase, which we tried to verify with density diagnostic measurements (see below).

3.2.3. Line Width

We also checked the variation of line width with time, which is shown in the bottom panels of Figures 9 and 10. The strongest enhancement in line width was observed in the flaring emission lines (Fe XXI and Fe XXIII) at $\sim 14:06$ UT when the first HXR peak and Doppler velocity peak in the hot plasma appear. We note that if the emission has a bulk Doppler-shifted velocity component, it will make the line broader due to the combination of the rest and moving components. However, at

the beginning of the flare, the Doppler velocity pattern of the lines can be fitted with a single Gaussian, and the whole lines are blue- or redshifted without a rest component (see, e.g., the line profiles of Fe XXIII and Fe XXIV in Figure 3 and Fe XXI in Figure 4). This implies that the enhanced line width at the beginning of the flare is related to non-thermal broadening, not Doppler velocity.

The non-thermal broadening in UV and X-ray emissions is usually regarded as a manifestation of unresolved mass motions of the plasma, such as multiple flows, turbulence, or waves (Alexander & MacKinnon 1993; Dere & Mason 1993; Chae et al. 1998; Hara et al. 2011; Kawate & Imada 2013). The significant enhancement of the line width and the HXR peak at the beginning of the flare are temporally well correlated. If the coronal reconnection occurs at the HXR peak timing, or the HXRs come from the accelerated electrons, the non-thermal broadening is possibly caused by turbulent motion or waves due to the magnetic reconnection or accelerated electrons.

There are several other peaks at different times in He II, Si IV, and Fe XII that appear to be related to small chromospheric brightenings, one of which may be a candidate for lower atmospheric reconnection that triggers the flare (Y. Bamba et al. 2016, in preparation).

3.2.4. Density

We measured the density of the bright kernel in the chromosphere and corona during the flare. Assuming the

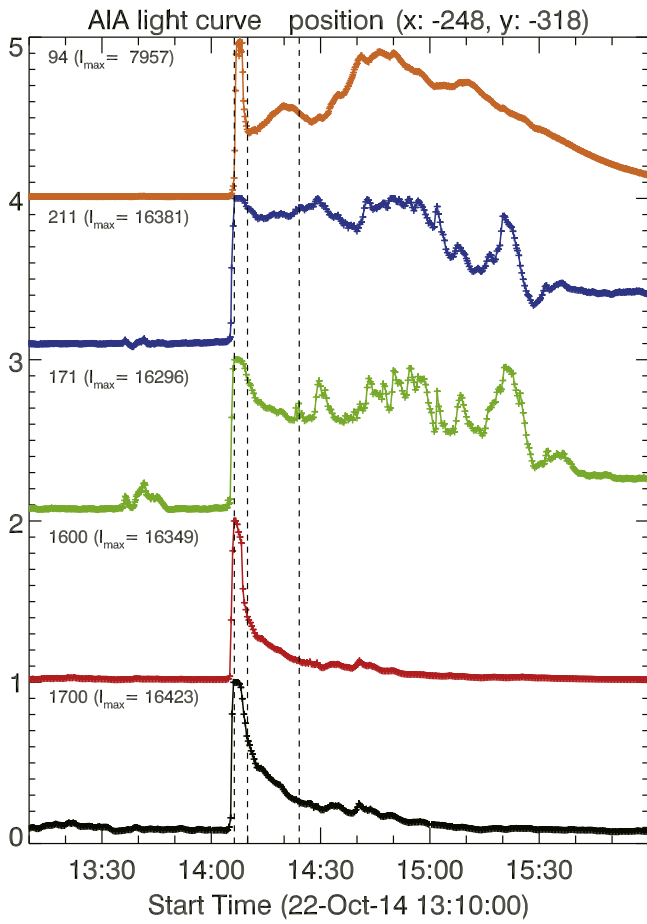


Figure 5. SDO/AIA light curves for the bright kernel. Intensities are normalized by the maximum intensity during the flare observation. The dashed vertical lines correspond to the same times marked in Figure 1.

plasma is optically thin, thermal, and in collisional ionization equilibrium, we derive the density using the intensity ratio of emission lines from the allowed and forbidden transitions, which are sensitive to the density. The diagnostic method is well described by Mariska (1992) and Phillips et al. (2008).

The good density-sensitive line pairs observed in EIS and IRIS are reported in Young et al. (2007) and Young (2015), respectively. We used the O IV line pair for measuring the density in the transition region plasma, and the Fe XIV line pair for the coronal plasma. Figure 12 shows the temporal variation of the density measured by IRIS (upper panel) and EIS (lower panel).

The O IV line pair (1399.77 Å and 1401.16 Å) shows density sensitivity in the range $\log N_e = 10\text{--}13$ with a range of intensity ratio of 0.17–0.43. We plotted the intensity ratio with time rather than the converted density because the intensity ratio during the impulsive phase of the flare exceeds the maximum value of the theoretical calculation. Therefore, we cannot measure the density during the impulsive phase. Before and after the impulsive phase, the averaged density is about $6.3 \times 10^{10} \text{ cm}^{-3}$. The enhanced intensity ratio during the impulsive phase implies densities in excess of 10^{13} cm^{-3} , which could be a result of compression from the explosive evaporation. Alternatively it could mean that the plasma is not in ionization equilibrium (Kafatos & Tucker 1972; Imada et al.

2011; Olluri et al. 2013; Martínez-Sykora et al. 2016) and therefore that the density measurements are invalid during that period. However, the ionization-relaxation time is only about 13 s for a plasma with the average density measured before and after the impulsive phase, which is much shorter than the duration for which the intensity ratio was enhanced.

Another possibility is that the measured line intensities are blended with cool lines, which was mentioned by Young (2015) and Polito et al. (2016). For example, Fe II 1399.96 Å, Si I 1401.51 Å, and unidentified lines at shorter wavelengths are close to O IV. Even if we perform multiple Gaussian fitting to take these blended lines into consideration, the intensity ratio is still enhanced during the impulsive phase.

We measured the coronal density with EIS using the Fe XIV 264.79 Å and 274.20 Å line pair. Compared to the results from O IV, Fe XIV shows that the density is slightly enhanced in the early phase of the flare, then increases significantly in the later phase and peaks at the same time as the SXR. The temporal variation of the density is similar to the intensity variation, suggesting that the low intensities observed when explosive evaporation occurs are due to the low density of the higher-temperature plasma. After evaporation, intensity enhancements can also be seen in the higher-temperature lines.

3.2.5. Chromospheric Temperature: Mg II Triplet Lines

We also checked the response of the chromospheric Mg II line. Figure 13 shows the Mg II line profile and the green horizontal lines mark the region we extracted for the spectral profile. The solid line shows the line profile during the impulsive phase (~14:07 UT) and the dotted line shows the spectrum around 12:00 UT when there is no specific brightening or X-ray response, as a reference. One interesting point to note is that the Mg II triplet lines emit strongly during the impulsive phase compared to during the non-flaring time.

Leenaarts et al. (2013) and Pereira et al. (2015) proposed that Mg II h & k and its subordinate lines (a triplet: 2791.60 Å, 2798.75 Å, and 2798.82 Å) can be used as diagnostic tools of the chromospheric plasma. In particular, Pereira et al. (2015) showed that the Mg II triplet blends at 2798.75 Å and 2798.82 Å will be seen in emission when chromospheric heating occurs, and the intensity ratio of line core to wing has a linear relationship with the increase in temperature.

We applied their quantitative method to investigate the changes in temperature in this flare kernel. We measured the intensity ratio of line core (the average intensity between 2798.66 and 2798.93 Å) to wing (taken at the 2799.32 Å) of the two blended Mg II triplet lines, 2798.75 Å and 2798.82 Å. The left panel in Figure 14 shows the variation of the intensity ratio with time. We converted the intensity ratio to ΔT using the linear relationship between them derived from the flare simulation conducted by T. M. D. Pereira (2017, private communication). The variation of ΔT with time is shown in the right panel of Figure 14. The estimated changes in temperature are about 3 kK for the flare kernel, and the temporal variation shows that the temperature increased suddenly at the beginning of the impulsive phase.

3.3. Summary of Results

1. The flare kernel is localized during the impulsive phase and the HXR emission, chromospheric intensity, and WL

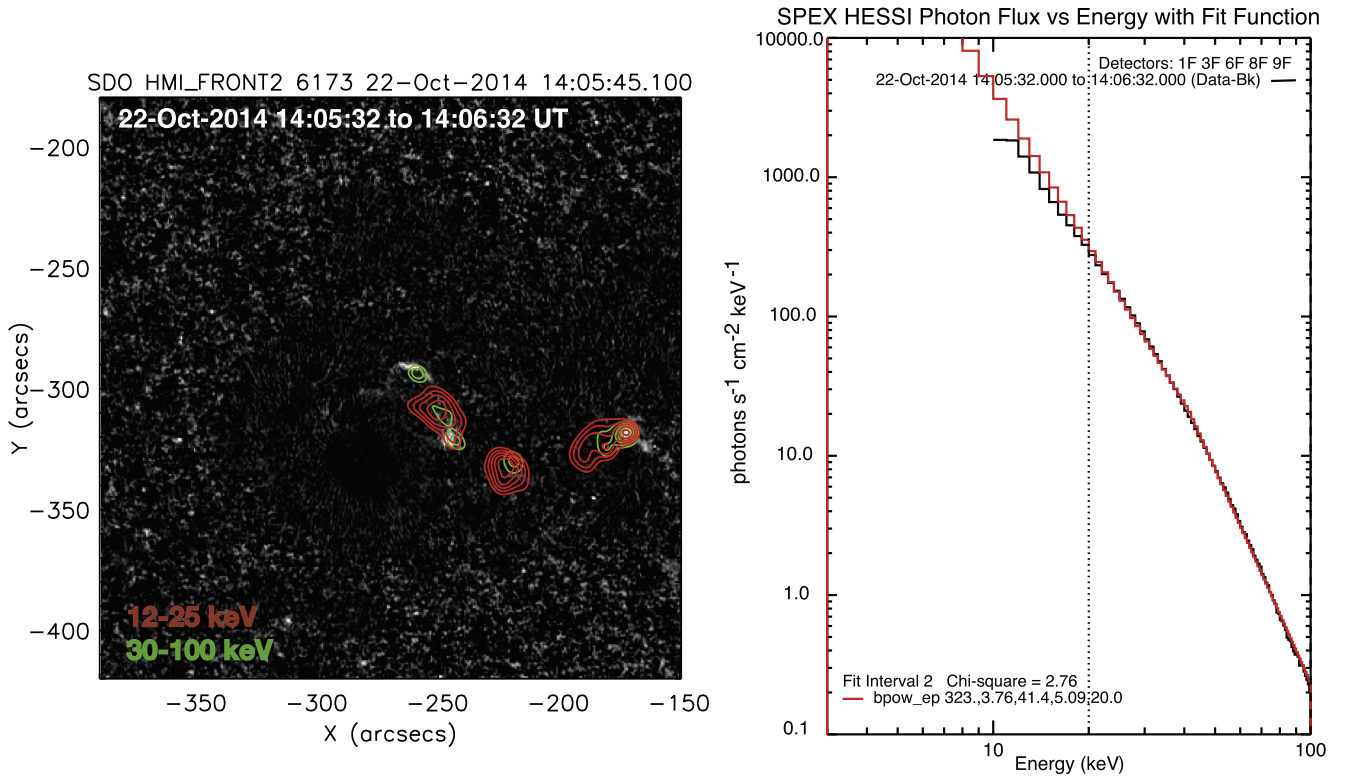


Figure 6. Left: HMI continuum difference image with HXR (30–100 keV) and SXR (12–25 keV) contours overlaid from the *RHESSI* cleaned image covering 14:05:32–14:06:32 UT. Red and green contours correspond to 50%, 60%, 70%, 80%, and 90% of the HXR and SXR intensity, respectively. Right: fitted *RHESSI* spectrum with energy for a flux in the energy range 20–100 keV during 14:05:32–14:06:32 UT. Black and red lines indicate the observed and fitted spectra, respectively.

continuum emission in the kernel are spatially and temporally correlated. The bright kernel peaks first in intensity in the WL continuum and O I, and then HXR and SXR emission peaks are observed consecutively.

2. The Doppler velocity and line width are enhanced during the impulsive phase. The strongest enhancement in line width appears during the first HXR peak, which is just after the WLF (within a minute). This may be a signature of turbulence from reconnection or heating by non-thermal electrons.
3. Chromospheric (O IV) and coronal (Fe XVI) density diagnostics show a strong enhancement during the impulsive phase. The temporal variation indicates that the density is enhanced first in the chromosphere and later in the corona. This is consistent with compression of the chromosphere, the Doppler velocity pattern, and the chromospheric evaporation process.
4. The Mg II subordinate line blend is seen in emission during the preflare and impulsive phase brightenings. The enhancement of the intensity ratio of the Mg II core to wing implies the existence of steep temperature gradients and heating in the low atmosphere (Pereira et al. 2015). At the time the WLF occurs, the ratio becomes over 10, suggesting that strong heating occurs in the lower atmosphere. Moreover, the strong enhancement of the ratio is correlated to the HXR peak, which implies that the nonthermally accelerated electrons detected as the HXR emission might be directly related to the low atmospheric heating.

4. Discussion

4.1. Spectroscopic Results Related to the Evaporation Flow and WLF

The flare kernel we discuss in this paper produced a WLF when the first HXR peak appeared. The correlation of the HXR peak and variation in Doppler velocity in this flare has already been reported by Li et al. (2015a) using *IRIS* observations, and they suggested that this implies that the flare is electron-driven and that energy deposition from non-thermal electrons produces the chromospheric evaporation flows and WLF.

From simulations of electron beam heating (Fisher et al. 1985a, 1985b, 1985c), it is expected that gentle or explosive evaporation should be observed, depending on the injected energy flux, and that it can be detected by examining the variation in velocity at different temperatures. When the energy flux injected is high, the simulation shows a blueshift in coronal lines, “*chromospheric evaporation*,” and a redshift in chromospheric lines, “*chromospheric condensation*.” This is called explosive evaporation. Conversely, if the injected energy is less than a critical value, about $F_{20} = 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$, gentle evaporation is observed, and most spectral lines are blueshifted.

Figure 11 shows that explosive evaporation occurs at this bright kernel in the impulsive phase. To confirm the relationship between the energy deposited by the accelerated electrons and the observed Doppler velocity pattern, we compared the deposited energy flux measured by *RHESSI* to the critical value of the energy flux in the simulations.

Assuming this WLF is produced by accelerated non-thermal electrons, we calculated the total power (P) in the non-thermal

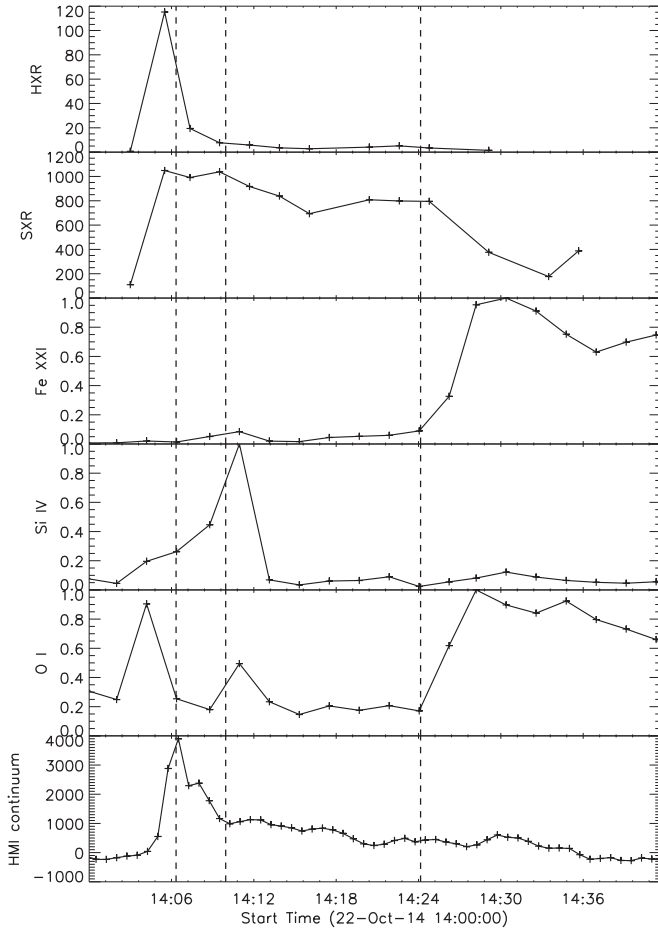


Figure 7. Light curves for the multi-wavelength observations: (a) *RHESSI* HXR, (b) *RHESSI* SXR, (c) *IRIS* Fe XXI, (d) Si IV, (e) O I, and (f) *SDO*/HMI continuum. The intensities from the *IRIS* spectra are normalized by the maximum intensity during the flare. The peak of the HMI continuum intensity is enhanced by around $3.8 \times 10^4 \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

electrons above a given electron energy (low cutoff energy) under the thick-target approximation using the equation (Hudson et al. 1978; Watanabe et al. 2010a)

$$P(\epsilon \geq \epsilon_c) = 4.3 \times 10^{24} \frac{b(\gamma)}{\gamma - 1} A \epsilon_c^{-(\gamma-1)} (\text{erg s}^{-1}). \quad (1)$$

For this purpose, we fit the *RHESSI* HXR photon spectrum. The right panel of Figure 6 shows the fitted *RHESSI* spectrum when explosive evaporation occurs (14:06 UT). ϵ_c is the low cutoff energy, γ is the spectral index, and $b(\gamma)$ is the auxiliary function from Brown (1971) for the relevant range of γ . To measure the energy flux, we determined the size of the HXR-emitting region where the HXR (30–100 keV) integrated intensity is greater than 60% of the maximum intensity. The calculated energy fluxes in the non-thermal electrons at the HXR peaks during the impulsive phase ($\sim 14:05$ and $14:11$ UT), assuming a cutoff energy of 30 keV, are about $7.7 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $6.1 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$, respectively (Figure 15). The energy of 30 keV is the lowest energy that contains a negligible amount of thermal emission yet still contains large fluxes of non-thermal photons. We also estimated the energy fluxes deposited by non-thermal HXR electrons above different threshold energies because we do not

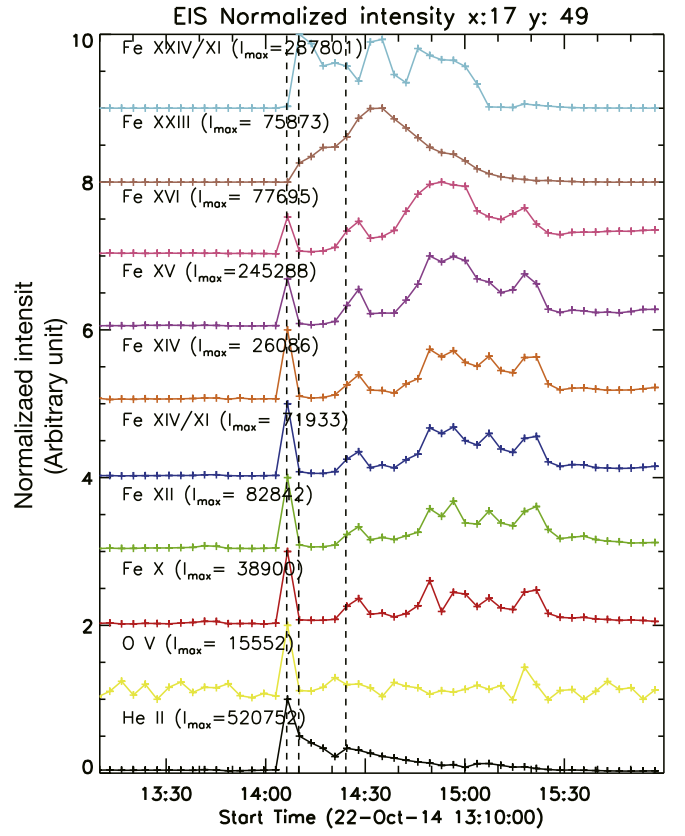


Figure 8. Temporal variation of the EIS spectral line intensities for the bright kernel. Intensities are normalized by the maximum intensity during the flare observation. The vertical dashed lines correspond to the times marked in Figure 1.

know the energy of the electrons that affected the WL emission. For example, non-thermal electrons in low energies cannot penetrate to the photosphere, which produces WL emission. On the other hand, the higher energy electrons may not transport enough energy due to the low photon flux. Even though we assume different threshold energies of 40 keV and 50 keV, the energy fluxes in the impulsive phase are about $3.0 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $1.4 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$, respectively. This shows that the energy deposited by the HXRs is strong enough to produce explosive evaporation and is consistent with the observed Doppler velocity pattern.

Furthermore, the flows from explosive evaporation are expected to have a reversal, where they change from downflow in the chromosphere to upflow in the corona, and our observations show such a reversal in the temperature range 0.5–2 MK. The velocities in this range also appear to be fairly steady. Interestingly, some downflows, of 5 km s^{-1} in the single Gaussian fits and 15 km s^{-1} when a double Gaussian is used, are observed in the coronal lines ($T \sim 2 \text{ MK}$), which is a surprisingly high temperature. A similarly high-temperature velocity reversal has previously been reported, however (Li & Ding 2011).

To explain the downflows in the coronal lines, Imada et al. (2015) investigated the dependence of the flow reversal temperature on different thermal conduction coefficients. It turns out that if the thermal conduction is strong, the energy is transported quickly by thermal conduction and this scenario

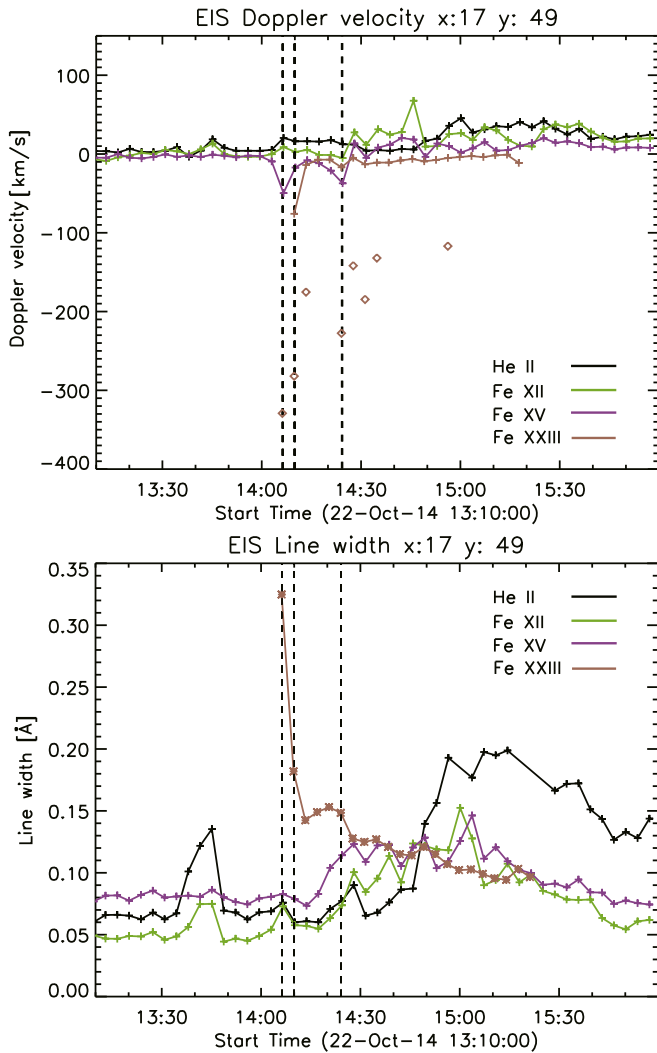


Figure 9. Temporal variation of the Doppler velocity (top) and line width (bottom) for the bright kernel from the EIS spectral lines: He II, Fe XII, Fe XV, and Fe XXIII. The vertical dashed lines correspond to the same times as shown in Figure 1.

shows similar characteristics to the electron beam-driven case. If the thermal conduction is weak, however, the energy is mainly transported by the enthalpy flux and advection. In this case, where enthalpy flux is dominant, the flow reversal temperature is much higher than in the thermal conduction case. In our observations, a strong redshift is seen at temperatures around 0.4 MK, and the Doppler velocities in the temperature range 0.5–2 MK are mostly steady. This implies that the flow reversal temperature in this flare is not very high, and is similar to that expected in the electron beam model. However, the Doppler velocity around 2 MK also shows small downflows, suggesting that we cannot neglect the possibility of energy transport by direct enthalpy flux, in addition to thermal conduction.

At the same time as the Doppler velocity peaks, enhanced line widths are observed at flaring temperatures. This may indicate the presence of turbulence from the non-thermal electrons or a reconnection process high in the corona since there is also a temporal correlation between the HXR emission and the peak in Doppler velocity. Most of the observations show that the electron beam heating model explains this flare, and the accelerated electrons can produce the WL continuum

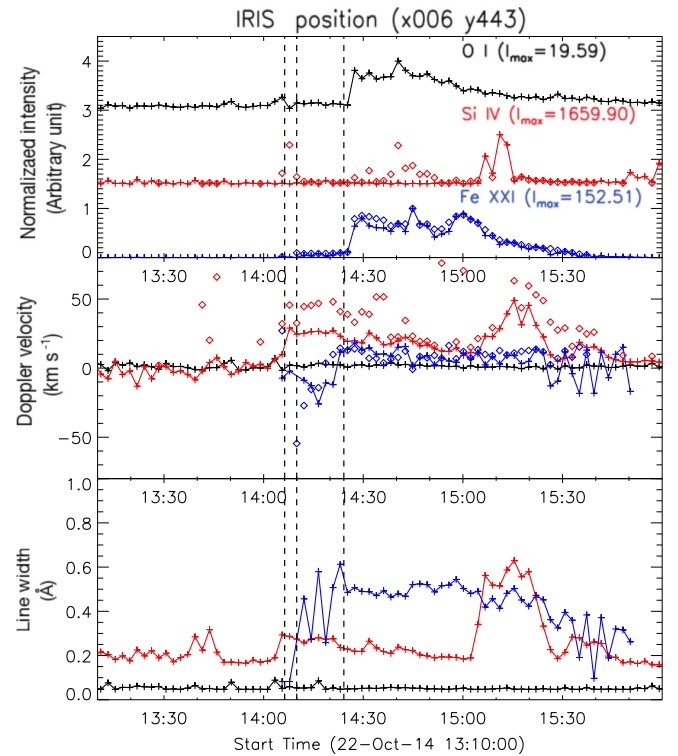


Figure 10. Temporal variation of the intensity (top), Doppler velocity (middle), and line width (bottom) for the bright kernel from the IRIS spectral lines: O I (black), Si IV (red), and Fe XXI (blue). Intensities are normalized by the maximum intensity during the flare observation. The vertical dashed lines correspond to the same times as shown in Figure 1.

emission. However, we cannot rule out the possibility of Alfvén waves as a heating mechanism (Fletcher & Hudson 2008), given the large non-thermal width in the lower-temperature lines, Fe XII and He II. Recently, Reep & Russell (2016) showed that Alfvén wave dissipation produces similar heating signatures to electron beam heating—for example, explosive evaporation and a significant temperature enhancement in the chromosphere. If Alfvén waves transport the energy flux to the low atmosphere, line widths can also be enhanced by the waves.

4.2. Comparison of RHESSI and IRIS Energy Fluxes

One of the important issues for understanding the WLF mechanism is how the energy is transferred to the lower atmosphere to produce the photospheric emission. Recently, it has been reported that not only strong flares but also weak flares (C-class flares) can produce WL emission (Matthews et al. 2003; Hudson et al. 2006). So it is important to know how much energy is dissipated in the chromosphere and whether the energy transferred by the electrons is enough to produce a WLF. Until recently, it has been difficult to estimate the energy flux in the chromosphere due to a lack of observations. Since the launch of IRIS, however, high-resolution spectroscopic observations of the chromosphere have become routine, and Pereira et al. (2015) suggested that the Mg II triplet could be used as a diagnostic tool for quantitatively measuring changes in temperature in the chromosphere.

We have measured the temperature changes during the flare using the Mg II triplet intensity ratio (Section 3.2.5), and used the results to estimate the energy flux deposited in the chromosphere in response to the flare. The Mg II h & k

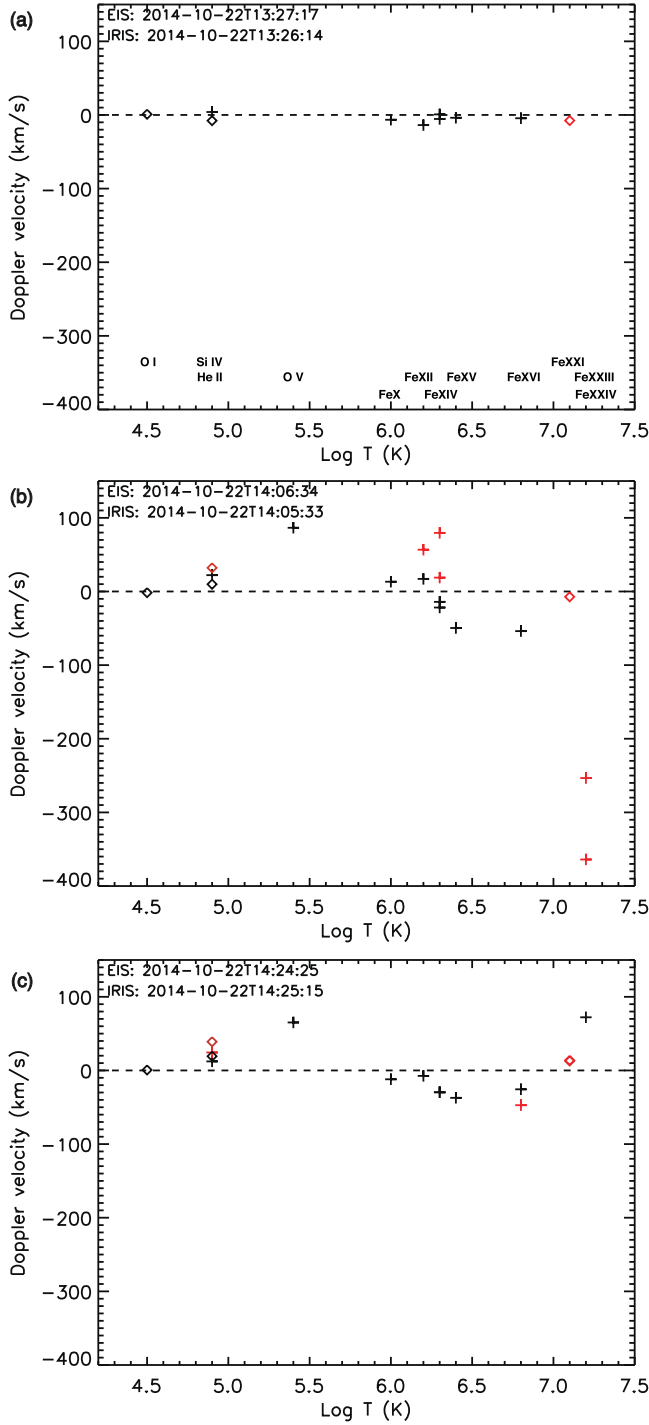


Figure 11. Doppler velocities from EIS and *IRIS* as a function of the peak formation temperature for the bright kernel at different times: (a) before the flare, (b) the impulsive phase, and (c) the gradual phase. Diamonds indicate the Doppler velocities from the *IRIS* spectra while crosses represent the Doppler velocities from the EIS spectra. Black and red indicate the velocities calculated from the single and multiple Gaussian components relative to the rest wavelengths. The element and ionization information of the spectral lines is noted at the bottom of panel (a).

components show similar peak intensities during the flare, implying that they might be in emission even though the plasma is optically thick. Furthermore, the densities measured using the O IV chromospheric line are strongly enhanced during the impulsive phase (Figure 12), which suggests that the plasma may be in local thermodynamic equilibrium (LTE). If

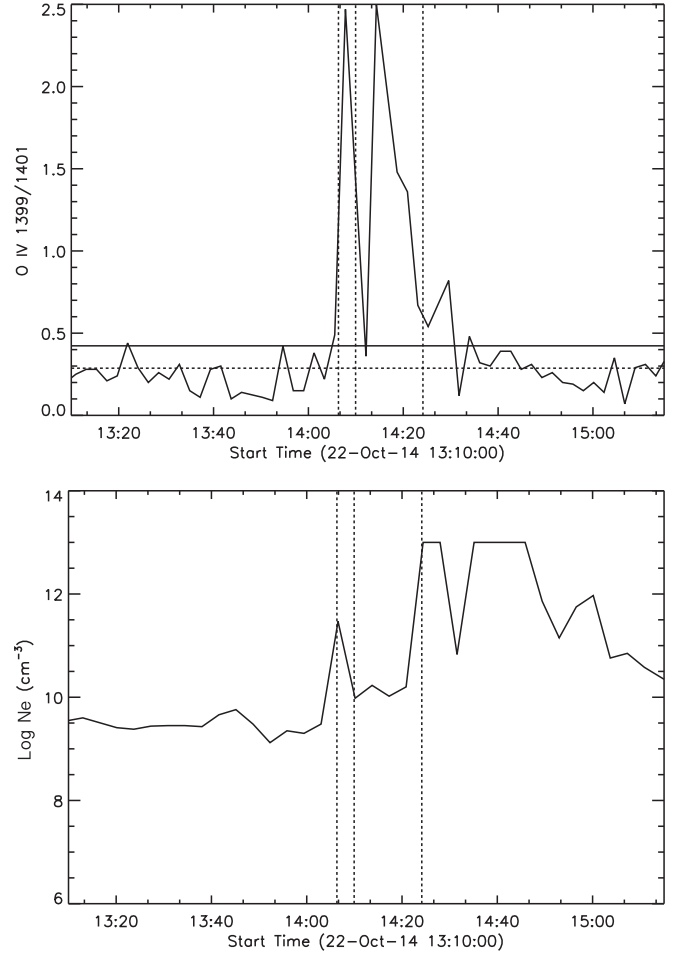


Figure 12. Top: temporal variation of the *IRIS* O IV 1399.8 Å/1401.2 Å intensity ratio for the bright kernel. The horizontal solid and dashed lines indicate the ratio of 0.43 ($\log N_e = 13$) in the high-density limit and the averaged intensity ratio before and after the impulsive phase, respectively. Bottom: temporal variation of the density measured from the EIS Fe XIV 264.79 Å/274.20 Å intensity ratio for the bright kernel. The vertical dashed lines indicate the times marked in Figure 1.

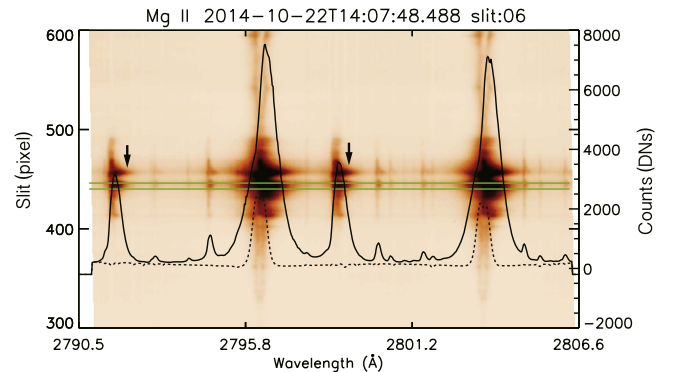


Figure 13. *IRIS* detector images of the Mg II h & k spectral windows overlaid with the averaged spectral line profiles at the location marked by the two horizontal green lines. The solid and dotted lines represent the line profiles during the impulsive phase and before the flare (around 12:00 UT), respectively. The arrows indicate the redshifts in the Mg II spectral lines.

we assume the plasma is optically thick and in LTE, the energy flux can be determined from the Stefan–Boltzmann law, $F = \sigma T_{\text{eff}}^4$. We estimate the temperature enhancement during the impulsive phase to be 3–3.3 kK (Figure 14), so the

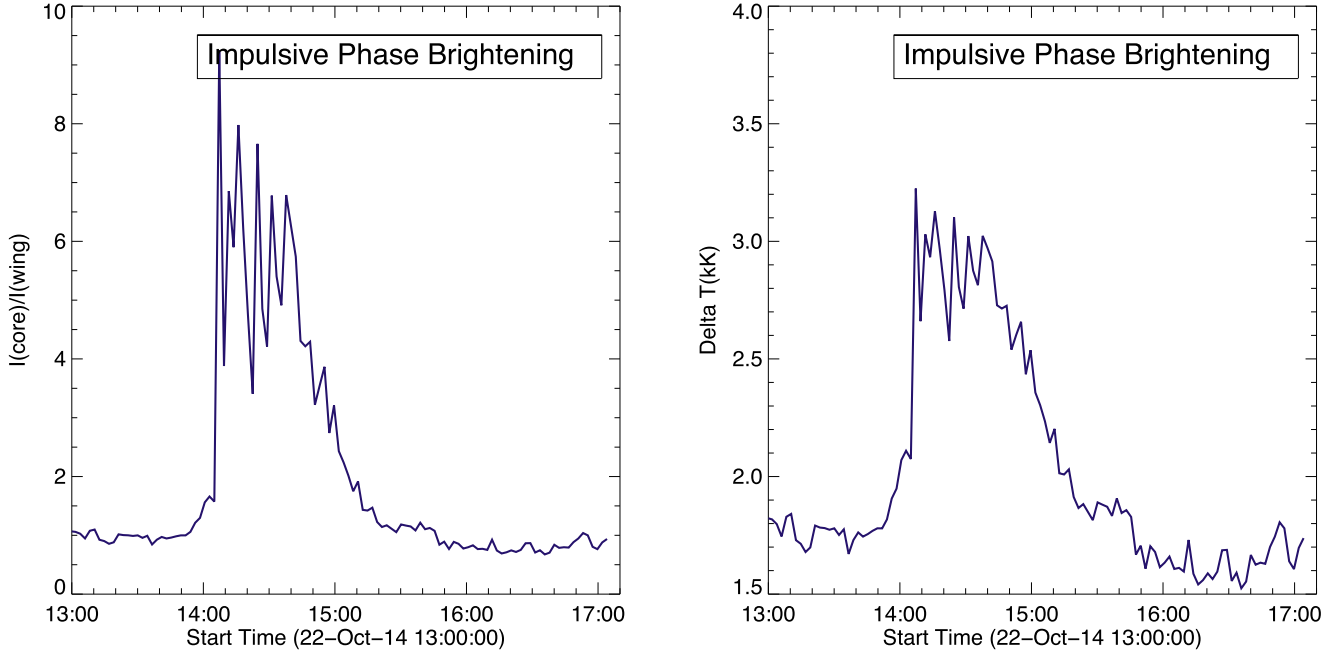


Figure 14. Left: temporal variation of the intensity ratio of the line core to wing of the two blended Mg II triplet lines, 2798.75 Å and 2798.82 Å, for the bright kernel. Right: temporal variation of the changes in temperature (ΔT) between the line core and wing formation regions for the bright kernel.

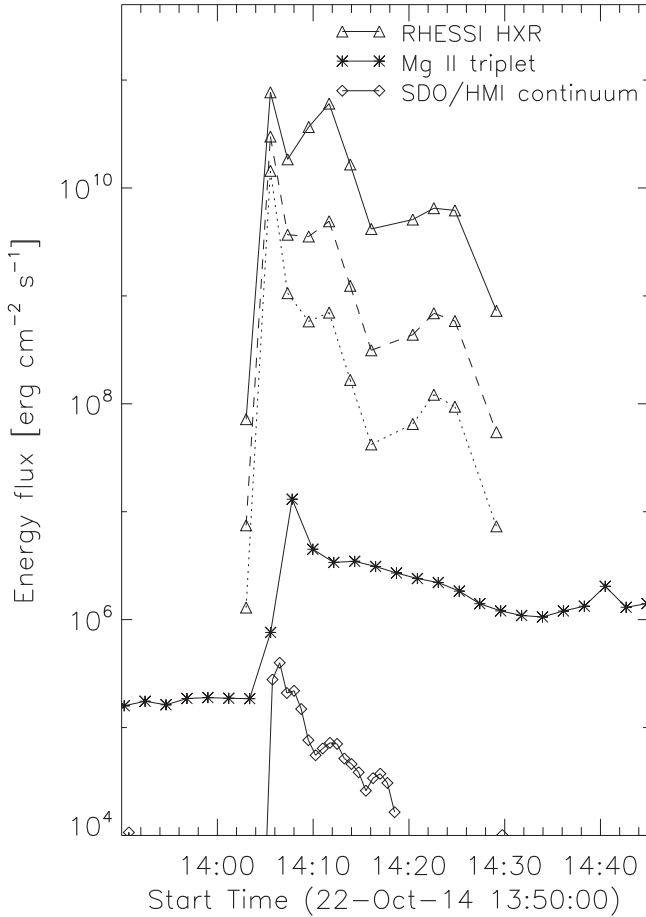


Figure 15. The energy flux of the bright kernel during the flare impulsive phase estimated from the *RHESSI* HXR emission with different threshold energies of 30 keV (solid line), 40 keV (dashed line), and 50 keV (dotted line), the Mg II triplet intensity observed by *IRIS*, and the WL continuum emission from *SDO/HMI*.

corresponding energy flux is $(4.6\text{--}6.7) \times 10^9 \text{ erg cm}^{-2} \text{ s}^{-1}$. Taking this energy flux as an estimate of the amount of energy dissipated in the chromosphere, it is about 6%–22% of the energy deposited by the accelerated non-thermal electrons as measured by *RHESSI*, assuming the cutoff energy of 30–40 keV. This result implies that the majority of the energy from the non-thermal electrons accelerated in the corona is still available to directly produce a WLF in this event.

Recently, Milligan et al. (2014) and Kleint et al. (2016) investigated the continuum enhancement across the EUV, UV, visible, and infrared during a flare, and compared it to the energy deposited by non-thermal electrons observed by *RHESSI*. In their investigation, Milligan et al. (2014) showed that 15% of the deposited energy is radiated by line and continuum emission in the lower atmosphere, and Kleint et al. (2016) found that 23% of the deposited energy is radiated by continuum emission. From their investigations, more than 60% of the energy is unaccounted for, and they suggested that it is dissipated by heating, plasma motions, or radiated away in other spectral regions or lines. Using *IRIS* and HMI continuum observations, we also measured the energy flux from the UV and WL continuum. We converted the observed Mg II DN to intensity using the *iris_get_response.pro* routine in SolarSoft and we calibrated the HMI intensity by comparison with the disk intensity reported in the atlas of Neckel (1994). We then estimated the radiated power, $P_\lambda = \pi I_\lambda A \Delta\lambda$, using the intensities (I_λ) and bandwidths ($\Delta\lambda$) of the *IRIS* and HMI continua. The energy fluxes from the *RHESSI* HXR, *IRIS* Mg II triplet, and HMI continuum are shown in Figure 15, and the energy fluxes in the UV and HMI continuum are only very small fractions of the power in the HXR emission. The estimated energy flux from dissipation by heating in the chromosphere may amount to $\sim 10\%$ of the deposited energy.

In this study, even though we have not performed any numerical modeling, we have been able to measure the changes in temperature in the chromosphere quantitatively using the

Mg II triplet observed by *IRIS*, as suggested by Pereira et al. (2015). This is the first attempt to apply this diagnostic technique to flare observations, and the results show that the changes in temperature in the chromosphere are about 3000 K, which is consistent with the results from the numerical modeling of the UV to IR spectra of Kleint et al. (2016). The results support their suggestion from numerical modeling that quite a strong temperature enhancement is needed in the chromosphere to produce noticeable continuum enhancement in the flare.

5. Summary

A bright kernel in an X1.6 flare on 2014 October 22 was observed by *Hinode*, *IRIS*, *SDO*, and *RHESSI*. The simultaneous observations covered the whole duration of the flare, and the bright kernel produces a multi-wavelength intensity enhancement from continuum to HXRs. We investigated the temporal variation of the spectral properties of this kernel and estimated the energy flux at different wavelengths.

The multi-wavelength spectroscopic observations show that the flare kernel is localized during the impulsive phase and the HXR emission, chromospheric intensity, and WL continuum emission in the kernel are spatially and temporally correlated. We found that explosive evaporation occurs and there are strong enhancements in line width during the first peak of the HXR emission, which is also coincident with the timing of the WLF. This may indicate that electron beam heating produces strong evaporation flows and there is turbulence from the reconnection or non-thermal electron heating. Furthermore, the Mg II subordinate line blend is in emission during the impulsive phase. The strong enhancement of the intensity ratio of the Mg II core to wing is correlated with the HXR peak, implying the existence of a steep temperature gradient and heating. The correlated temporal variations of the HXR, WL, explosive evaporation flows, and the Mg II line response, together with the comparison of the energy flux through the corona to the chromosphere, imply that the flare heating and evaporation flow are driven by non-thermal electrons, though we cannot rule out a possible contribution from Alfvén wave heating.

We have also estimated the energy flux in the bright kernel using the intensities and changes in temperature in the chromosphere. Comparison of the energy deposited in the corona and the energy dissipated in the chromosphere shows that accelerated electrons dissipate only $\sim 20\%$ of their energy in the chromosphere and the remaining energy is enough to directly produce WLF emission in the photosphere. The flare we investigated is quite strong—X1.6 class—so while the accelerated non-thermal electrons from this strong flare could produce a WLF directly in this event, we still do not know whether most WLFs can be produced by the energy from the accelerated electrons or whether this process works even in small flares. Therefore, further studies applying similar techniques to other flares that produce WL emission are needed to confirm whether they can also be produced directly or not.

Data are courtesy of the science teams of *Hinode*, *IRIS*, *RHESSI*, and *SDO*. *Hinode* is a Japanese mission developed and launched by ISAS/JAXA, with NAOJ as domestic partner and NASA and STFC (UK) as international partners. It is operated by these agencies in cooperation with ESA and the NSC (Norway). *IRIS* is a NASA Small Explorer (SMEX)

mission developed and operated by LMSAL with mission operations executed at NASA Ames Research center and major contributions to downlink communications funded by ESA and the Norwegian Space Centre. The *RHESSI* satellite is a NASA SMEX mission. HMI and AIA are instruments on board *SDO*, a mission for NASA's Living With a Star program. This work was supported by JSPS KAKENHI Grant Numbers JP25220703 (PI: S. Tsuneta), JP15K17622, and JP16H01187. The work of K.-S.L. was carried out by the joint research program of the Institute for Space–Earth Environmental Research (ISEE), Nagoya University. The work of S.I. was supported by JSPS KAKENHI Grant Numbers JP23340045, JP26287143, JPG2602, and JP15H05816. The work of D.H.B. was performed under contract with the Naval Research Laboratory and was funded by the NASA *Hinode* program.

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