THE RELATIONSHIP BETWEEN EXTREME ULTRAVIOLET NON-THERMAL LINE BROADENING AND HIGH-ENERGY PARTICLES DURING SOLAR FLARES

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Received 2013 April 11; accepted 2013 August 6; published 2013 September 13

ABSTRACT

We have studied the relationship between the location of EUV non-thermal broadening and high-energy particles during large flares using the EUV Imaging Spectrometer on board Hinode, the Nobeyama Radioheliograph, and the Atmospheric Imaging Assembly on board the Solar Dynamic Observatory. We have analyzed five large flare events that contain thermal-rich, intermediate, and thermal-poor flares classified by the definition discussed in the paper. We found that, in the case of thermal-rich flares, the non-thermal broadening of Fe XXIV occurred at the top of the flaring loop at the beginning of the flares. The source of 17 GHz microwaves is located at the footpoint of the flare loop. On the other hand, in the case of intermediate/thermal-poor flares, the non-thermal broadening of Fe XXIV occurred at the footpoint of the flare loop at the beginning of the flares. The source of 17 GHz microwaves is located at the top of the flaring loop. We discussed the difference between thermal-rich and intermediate/thermal-poor flares based on the spatial information of non-thermal broadening, which may provide clues that the presence of turbulence plays an important role in the pitch angle scattering of high-energy electrons.

Key words: magnetohydrodynamics (MHD) – plasmas – shock waves – Sun: corona – Sun: flares – Sun: UV radiation

Online-only material: color figures

1. INTRODUCTION

Particle acceleration has been discussed as one of the long-standing problems in astrophysical plasmas. It is often observed that high-energy particles are generated with explosive energy releases such as supernova explosions, solar flares, and substorms in Earth’s magnetosphere. Several observations indicate that the energy spectrum in the high-energy range can be described by a power-law distribution. Many theoretical and observational studies have been carried out to understand the origin of high-energy particles and various mechanisms have been proposed such as shock acceleration (e.g., Blandford & Ostriker 1978). Recently, magnetic reconnection has been thought to be important for particle acceleration because high-energy particles are observed in association with magnetic reconnection. For example, in Earth’s magnetosphere, energetic particles are often observed in the vicinity of magnetic reconnection regions (e.g., Sarris et al. 1976; Øieroset et al. 2002; Imada et al. 2007, 2011).

Solar flares, which are also believed to be associated with magnetic reconnection (e.g., Carmichael 1964; Svirskii 1966; Hirayama 1974; Kopp & Pneuman 1976; Pneuman et al. 1981), are another important field of particle acceleration. The solar atmosphere is an excellent space laboratory for particle acceleration because of its observability on large scales. Over the last several decades, considerable effort has been devoted toward understanding high-energy particles during solar flares. In the last two decades, there have been substantial advances in the study of particle acceleration, mainly due to modern satellite observations in hard X-rays (HXR); for example, the Hard X-ray Telescope on board Yohkoh (Kosugi et al. 1991) and RHESSI (Lin et al. 2002). Masuda et al. (1994) discussed the location of HXR sources and they concluded that the HXR sources are located above the flare loops that are observed in the soft X-ray (SXR) range. This result indicates that magnetic reconnection occurred above the SXR flare loops and that the high-energy particles might be accelerated downstream of the reconnection outflow. After the work of Masuda et al. (1994), several investigations of the particle acceleration mechanisms were intensively carried out. There are essentially three major mechanisms for particle acceleration during solar flares: (1) DC electric field acceleration (e.g., Kliem 1994), (2) stochastic acceleration (e.g., Melrose 1974), and (3) shock acceleration (e.g., Tsuneta & Naito 1998). The most plausible mechanism to explain the observed high-energy particles is still under discussion. However, in most mechanisms, even including those based on DC electric field acceleration (e.g., Ambrosiano et al. 1988), the wave and/or turbulence play an important role in the particle acceleration. Therefore, many people believe that understanding the characteristics of waves and/or turbulence in the course of solar flares is crucial for understanding the particle acceleration mechanism.

Waves and/or turbulence in the solar corona are often discussed based on spectroscopic observation in the extreme-ultraviolet (EUV) or SXR wavelength range. The spectral line width obtained from spectroscopic observations mainly consists of three parts: (1) the thermal width, (2) the instrumental width, and (3) the non-thermal width. It is generally believed that the non-thermal width is associated with waves/turbulence or velocity gradients (e.g., Doschek et al. 2007; Imada et al. 2009). The non-thermal width is expressed by the following formula:

$$W_N = \sqrt{W_{\text{obs}}^2 - W_I^2 - 4 \ln 2 \frac{2kT_i}{M_i}} \quad (1)$$

where $W_N$ is the non-thermal width, $W_{\text{obs}}$ is the observed line width, $W_I$ is the instrumental line width, $k$ is the Boltzmann constant, $T_i$ is the ion temperature, and $M_i$ is the ion mass.
Non-thermal line broadening during solar flares in SXR emission lines ($\sim 10^7$ K) has been reported by Solar Maximum Mission (SMM)/bent crystal spectrometer (BCS; Rapley et al. 1977) or Yohkoh/Bragg crystal spectrometer (BCS; Culhane et al. 1991) observations. After their discovery, the characteristics of non-thermal line broadening have been intensely studied to clarify their origin. In Mariska et al. (1993), the authors divided the flares into rising and decaying phases for 219 flare events observed by Yohkoh/BCS and they concluded that there is no correlation between the line width of Ca xix and the heliocentric distance, the peak intensity, the rising phase duration, or the total flare duration. On the other hand, there is a weak correlation between the line width and the Doppler shift at the rising phase of the flares. Mariska & McTiernan (1999) studied 48 limb flares that contained occulted and non-occulted flares and they found that there is no difference in the line width between the occulted and non-occulted flares. Harra-Murnion et al. (1997) analyzed the small GOES class flares and found that the line width does not correlate with the flare size, the complexity, or the HXR intensity. However, the line width weakly correlates with the total and rising duration of the flares. From the observational results of SMM/BCS and Yohkoh/BCS, Ranns et al. (2000) proposed that the origin of non-thermal line broadening during solar flares is turbulence at one of the following positions: (1) the reconnection site, (2) above the looptop (HXR sources), (3) the SXR looptop, (4) the evaporating chromospheric plasma, and (5) the flare loop footpoint. Furthermore, Ranns et al. (2001) analyzed 59 limb flares using the Ca xix line of Yohkoh/BCS and HXRs of the Burst and Transient Source Experiment. They found that the line broadening occurs after the HXR burst in the case of impulsive flares. On the other hand, the line broadening occurs before the HXR burst in long duration flares. Thus, Ranns et al. (2001) concluded that line broadening comes from turbulent evaporation at the footpoint in the case of impulsive flares. However, the line broadening comes from looptop turbulence during the preflare phase in the case of long duration flares.

So far, various observational studies of non-thermal line broadening have been reported. However, most of studies are not based on spatially resolved observations but instead on observations integrated over the Sun. Thus, there are no observational studies that directly discuss the relationship between the location of the EUV non-thermal line broadening and high-energy particles during solar flares. Recently, the Hinode spacecraft (Kosugi et al. 2007) carrying three telescopes, the Solar Optical Telescope, the X-Ray Telescope, and the EUV Imaging Spectrometer (EIS), was launched. EIS is a high spectral resolution spectrometer aimed at studying dynamic phenomena in the corona with high spatial resolution and sensitivity (Culhane et al. 2007). Thus, by using EIS observations, we can directly investigate the location of the non-thermal line broadening. Watanabe et al. (2008) found line broadening at the looptop during a C4.2 flare observed with EIS imaging spectroscopy. Hara et al. (2008) also reported the line broadening of Ca xvii at the looptop in a C class long duration event. On the other hand, Imada et al. (2008) and Milligan (2011) found line broadening at the footpoint. They argued that the origin of the line broadening might be chromospheric evaporation.

In this paper, we discuss the relationship between the location of EUV non-thermal broadening and high-energy particles during the large flares. We also pay attention to the relationship between the location of non-thermal broadening and flare characteristics such as thermal richness and/or duration. In Section 2, we introduce the flare data and the result of analyses on two typical flares. In Section 3, we show the results of other flare events to verify the results that are discussed in Section 2; we also discuss the relationship between the location of non-thermal broadening and high-energy electrons. In Section 4, we summarize our observational results and discuss the interpretation of the relationship between non-thermal broadening and high-energy particles.

## 2. OBSERVATIONS

### 2.1. Data

We carry out a comprehensive analysis to clarify the relationship between the location of EUV non-thermal broadening and high-energy particles during large flares. We analyze multi-wavelength data obtained from Hinode/EIS, the Nobeyama Radioheliograph (NoRH; Nakajima et al. 1994), the Nobeyama Radio Polarimeter (NoRP; Nakajima et al. 1985, 1994), and the Solar Dynamics Observatory/Atmospheric Imaging Assembly (AIA; Lemen et al. 2012). By using the Hinode Flare Catalogue (Watanabe et al. 2012), we searched for large solar flare events (larger than GOES M class) observed simultaneously by the instruments listed above from 2010 to 2012. We carefully checked the data from the onset phase to the impulsive phase and excluded event with maximum brightness temperatures at 17 GHz less than $10^8$ K because of the failure level of image reconstruction. We also used the Nobeyama Radioheliograph Event List to avoid very low flux events at microwave frequencies. In the end, we find five events that are suitable for our purposes. We label the events (a), (b), (c), (d), and (e) according to the time of occurrence (Table 1). Figure 1 shows the light curves of GOES 1.0–8.0 Å SXR fluxes and NoRP 17 GHz fluxes during the flare events. It can be seen that events (a), (b), and (e) are impulsive flares that have a sharp peak at microwave frequencies; events (c) and (d) are long duration flares.

All that EIS data that we use in this paper are sparse raster scanning observations. The scanning step is 5 arcsec, although the slit width is 2 arcsec. The exposure time is 8 s except for one flare event (2012 July 14; 9 s). It takes $\sim$6 minutes to obtain one scanning image ($180 \times 152$ arcsec$^2$). The EIS data from the raster are processed using the EIS team-provided software (eis_prep), which corrects for the flat field, dark current, cosmic rays, and hot pixels. The slit tilt was corrected by the eis_tilt correction. Due to the thermal deformation of the instrument, there is an orbital variation in the line position that causes an artificial Doppler shift of $\pm 20$ km s$^{-1}$, which follows a sinusoidal behavior. This orbital variation in the line position was corrected for using the house keeping data (Kamio et al. 2010). We assume the instrumental line width ($W_i$) in Equation (1) is equal to 0.061 Å for the short wavelength band and 0.062 Å for the long wavelength band. Our results are not

| Event | Microwave Peak Time | Flare Position | GOES Class | TEI |
|-------|---------------------|----------------|------------|-----|
| (a)   | 2011 Feb 16 01:36:53 | (373, −241)    | M1.0       | 0.06|
| (b)   | 2011 Sep 23 23:53:53 | (−859, 162)    | M1.9       | 0.05|
| (c)   | 2011 Sep 25 02:32:35 | (−707, 147)    | M4.4       | 0.73|
| (d)   | 2011 Sep 25 04:52:55 | (−653, 98)     | M7.4       | 0.58|
| (e)   | 2012 Jul 14 04:54:48 | (319, −319)    | M1.0       | −0.52|

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1. http://solar.nso.edu/solar Maxi-
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4. http://solar.nso.edu/solar Maxi-
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sensitive to this assumption, because the non-thermal line width in the high temperature range is large enough to be distinguished from the instrumental width during solar flares. In this paper, we only use the Fe xxiv line at 192.03 Å in the EIS data, because we focus on the characteristics of non-thermal broadening at high temperatures. Fe xxiv is one of the highest temperature lines observed by EIS. The typical temperature of Fe xxiv is $2 \times 10^7$ K. Therefore, we can compare our results with past results that discuss non-thermal broadening using high-temperature emission lines (e.g., Ca xix: $T_e \sim 3 \times 10^7$ K; Ranns et al. 2001).

We use AIA 131 Å data to discuss the temporal evolution of the flare loop. The 131 Å images contain Fe viii and Fe xxi lines and Fe xxi emission generally dominates during the large flares. Therefore, we can easily compare the AIA 131 Å and EIS 192.03 Å images, because the temperature sensitivities are almost the same. We also use AIA 1700 Å data to trace the flare ribbons. All AIA data are processed by aia_prep.

The characteristics of high-energy particles can be discussed using NoRH and NoRP data. NoRH data are taken every 1 s with a spatial resolution of about 10 arcsec. The 17 GHz microwave flux emitted from high-energy electrons trapped within the flare loop is observed as the gyrosynchrotron radiation. Thus, we can discuss the temporal evolution of high-energy particles from the NoRH 17 GHz flux. There is no spatial resolution for the NoRP data. Although the temporal resolution of the data is 0.1 s, we integrate the data over 10 s to reduce noise. We use the GOES SXR flux and the NoRH 17 GHz microwave data to classify the thermal richness of the flare event. From Kawate et al. (2011), there is a positive correlation between the SXR flux and the 17 GHz flux in a logarithmic scale; Kawate et al. (2011) discussed the thermal richness from the ratio between the GOES SXR flux and the NoRH 17 GHz microwave flux. Kawate et al. (2011) defined the thermal emission index (TEI) to discuss the thermal richness of flares:

$$\text{TEI} = \log_{10} \frac{I_{\text{GOES} \frac{0.5}{17 \text{GHz}}}}{I_{17 \text{GHz}}} + 6.16. \quad (2)$$

In the statistical study of Kawate et al. (2011), long duration events generally tend to have positive TEI values. On the other hand, short duration events tend to have negative TEI values. In this paper, we use TEI for classifying the flare thermal richness. We define TEI $> 0.2$ as thermal-rich, $0.2 > \text{TEI} > -0.2$ as intermediate, and $-0.2 > \text{TEI}$ as thermal-poor flares. The flare events (a) and (b) can be classified as intermediate flares, events (c) and (d) can be classified as thermal-rich flares, and event (e) can be classified as a thermal-poor flare (Table 1).

2.2. Intermediate Flares (Event (b))

On 2011 September 23, a large solar flare (GOES M1.9, peak time 23:56) occurred in the northeast part of the Sun (12°N, 56°E). The maximum NoRH 17 GHz flux was 225 sfu. NoRP 17 GHz, GOES 1.0–8.0 Å, and RHESSI 25–50 keV light curves are shown in Figure 2 with a solid line, a dashed line, and a dotted line, respectively. The GOES light curve has a sharply rising phase (~3 minutes), which is a typical characteristic of an impulsive flare event. The light curve at microwave frequencies or HXRs has a sharp peak (~1 minute), which is also a typical characteristic of an impulsive flare event.
The TEI estimated by Equation (2) is 0.05, which classifies these events as intermediate flares.

First, we analyze the temporal evolution of high temperature plasma over the entire flare region using the Fe xxiv line at 192.03 Å. We integrate the line profile over the EIS field of view (FOV). Figure 3 shows an example during the flare of the line profile integrated over the EIS FOV with Gaussian fitting. We can obtain the intensity and non-thermal velocity from the integrated line profile. We call these quantities the full-FOV intensity and the full-FOV non-thermal velocity. The line profile is integrated from 191.90 to 192.15 Å to obtain the intensity. The full-FOV intensity and full-FOV non-thermal velocity are suitable for describing the temporal evolution of the entire flare plasma, although they do not contain any spatial information. Furthermore, they can be easily compared with past results obtained from non-spatially resolved telescopes such as Yohkoh/BCS. Figure 4 shows the temporal variation of the full-FOV intensity (solid line), the full-FOV non-thermal velocity (horizontal line), and the microwave intensity (dotted line). The length of the horizontal line in Figure 4 (the full-FOV non-thermal velocity) represents the scanning duration for one raster image. The non-thermal velocities are plotted when the line peak is over 1000 erg cm\(^{-2}\) s\(^{-1}\) str\(^{-1}\) Å\(^{-1}\) to avoid overestimating the line width due to contamination from Fe v iii and Fe xi around 192.03 Å. As we mentioned before, the Fe xxiv 192.03 Å line is very strong during the flare. Therefore, with these criteria, we can easily avoid contamination effects. The full-FOV non-thermal velocity of Fe xxiv shows values larger than 200 km s\(^{-1}\) during the microwave burst, and these values gradually reduce with time. On the other hand, the full-FOV intensity of Fe xxiv peaked after the microwave burst. The GOES light curve also peaked after the microwave burst (23:56). We cannot decide whether the full-FOV non-thermal velocity peaked before or after the microwave burst, because the EIS raster scanning took a longer time than the typical microwave burst duration. However, it is remarkable that the full-FOV non-thermal velocity peaked before the peak of the full-FOV intensity.

Next, we study the Fe xxiv line profiles that are not spatially integrated. We are interested in the location of the non-thermal broadening at this time. Figure 5 shows the intensity, the velocity, and the non-thermal velocity of the Fe xxiv line calculated with Gaussian fitting during the impulsive phase. We calculate the non-thermal velocity only in the case that the intensity is larger than 5 × 10\(^4\) erg cm\(^{-2}\) s\(^{-1}\) str\(^{-1}\) Å\(^{-1}\) to avoid the contamination of Fe v iii and Fe xi, which we discussed above already. In Figure 5, green contours show non-thermal velocities of 100, 140, and 180 km s\(^{-1}\). The maximum intensity and the maximum non-thermal velocity are almost cospatial. Furthermore, the northern part of the non-thermal broadening is roughly cospatial with the blueshifted region (∼150 km s\(^{-1}\)) of the velocity of Figure 5.

Finally, we study the relationships among the locations of the non-thermal broadening, the flare loop, and the flare ribbon. We also discuss the temporal evolution of these relationships. The temporal evolution of the relationships among the flare loop, the flare ribbon, and the non-thermal broadening is shown in Figure 6. The color image, the green contours, and the black contours show the AIA 131 Å intensity, the non-thermal velocity of EIS data at 192.03 Å, and the AIA 1700 Å intensity, respectively. The contour levels of the non-thermal velocity are variable. In each panel of Figures 6(i)–(iv), the EIS raster scanning starts from 23:49:33, 23:55:23, 00:01:12, and 00:07:01, respectively. At the beginning of the flare (∼the microwave peak), the non-thermal broadening (green contours) and the flare ribbons (black contours) were cospatial. The location of non-thermal broadening gradually moved toward the looptop.

2.3. Thermal-rich Flares (Event (d))

On 2011 September 25, a large solar flare (GOES M7.4, peak time 04:50) occurred in the northeast part of the Sun (13°N, 50°E). The maximum NoRH 17 GHz flux was 283 sfu. NoRP 17 GHz, GOES 1.0–8.0 Å, and RHESSI 25–50 keV light curves are shown in Figure 7 with a solid line, a dashed line, and a dotted line, respectively. The GOES light curve has a gradually rising phase (∼20 minutes), which is a typical characteristic of a long duration flare event. The light curve at microwave frequencies or HXRs has a gradual peak (∼5 minutes), which is also a typical characteristic of a long duration flare event. The TEI estimated by Equation (2) is 0.58, which classifies these events as thermal-rich flares.

We analyze thermal-rich flares in the same way as the intermediate flares discussed in the previous subsection. Figure 8 shows an example during the flare of the line profile integrated over the EIS FOV with Gaussian fitting. Figure 9 shows the temporal variation of the full-FOV intensity (solid line),
Figure 5. Fe xxiv intensity (erg cm$^{-2}$ s$^{-1}$ str$^{-1}$ Å$^{-1}$), velocity (km s$^{-1}$), and non-thermal velocity (km s$^{-1}$) at the peak time of the non-thermal velocity (see Figure 4) during the intermediate flare. Green contours represent non-thermal velocities of 100, 140, and 180 km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 6. Temporal evolution of the non-thermal line broadening during the intermediate flare. The color image, the green contours, and the black contours correspond to the AIA 131 (Å) intensity map, the non-thermal velocity of Fe xxiv (192.03 Å), and the AIA 1700 (Å) intensity, respectively.

(A color version of this figure is available in the online journal.)

the full-FOV non-thermal velocity (horizontal line), and the microwave intensity (dotted line). The full-FOV non-thermal velocity of the Fe xxiv line gradually increased during the rising phase of the flare and reached $\sim$150 km s$^{-1}$ during the microwave burst. After the microwave burst, it gradually reduced with time. The full-FOV intensity of Fe xxiv (04:46) and GOES (04:50) also peaked at the microwave burst. We cannot decide whether the full-FOV non-thermal velocity
peaked before or after the microwave burst because the EIS raster scanning took a longer time than the typical microwave burst duration. However, it is remarkable that the full-FOV non-thermal velocity and the full-FOV intensity of the Fe xxiv line simultaneously peaked around the microwave burst.

Next, we study the Fe xxiv line profiles that are not spatially integrated. Figure 10 shows the intensity, the velocity, and non-thermal broadening (green contours) is always observed around the looptop (or above the looptop). The non-thermal broadening seems to be located apart from the flare ribbons. The location of the non-thermal broadening gradually moved to higher locations associated with the growth of the flare loop.

2.4. Comparison with Intermediate and Thermal-rich Flares

The intermediate flare observed on 2011 September 23 shows typical characteristics of an impulsive flare. The GOES light curves and high-energy electrons show a sharp peak. The full-FOV non-thermal velocity of Fe xxiv peaked before the peak of the full-FOV intensity of Fe xxiv and GOES. The location of the non-thermal broadening is cospatial with the flare ribbons at the beginning of the flare. After the microwave peak, the location of non-thermal broadening gradually moved toward the looptop.

The thermal-rich flare observed on 2011 September 25 shows typical characteristics of a long duration flare. The GOES light curves and the high-energy electrons show a gradual rising phase. The full-FOV non-thermal velocity of Fe xxiv simultaneously peaked with the full-FOV intensity of Fe xxiv and GOES. At the beginning of the flare, the location of non-thermal broadening is located at the looptop or above the looptop far from the flare ribbons. During the flare, the non-thermal broadening is always located at the looptop or above the looptop.

The main difference between the intermediate and thermal-rich flare is the location of the non-thermal broadening at the beginning of the flare. The non-thermal broadening starts from the footpoints of the flare loop in the case of the intermediate flare, although the broadening starts at the looptop of the flare loop in the case of the thermal-rich flare. The timing between the
Figure 10. Fe xxiv intensity (erg cm$^{-2}$ s$^{-1}$ str$^{-1}$ Å$^{-1}$), velocity (km s$^{-1}$), and non-thermal velocity (km s$^{-1}$) at the peak time of the non-thermal velocity (see Figure 9) during the thermal-rich flare. Green contours represent non-thermal velocities of 100, 140, and 180 km s$^{-1}$.

(A color version of this figure is available in the online journal.)

Figure 11. Temporal evolution of the non-thermal line broadening during the thermal-rich flare. The color image, the green contours, and the black contours correspond to the AIA 131 (Å) intensity map, the non-thermal velocity of the Fe xxiv line (192.03 Å), and the AIA 1700 (Å) intensity, respectively.

(A color version of this figure is available in the online journal.)
full-FOV non-thermal broadening and the full-FOV intensity of Fe\textsc{xxiv} is also different between the intermediate and the thermal-rich flares. The full-FOV non-thermal velocity peaked before the peak of the full-FOV intensity in the case of the intermediate flare, although the full-FOV non-thermal velocity and the full-FOV intensity peaked simultaneously.

3. OTHER FLARES AND MICROWAVE SOURCES

We investigate the same analysis for more three events to verify the results that were discussed in the previous section. We carry out a full-FOV analysis in the same way to clarify the temporal evolution of high temperature plasmas over the entire flare region using the Fe\textsc{xxiv} line at 192.03 Å. In event (a), which can be classified as an intermediate flare, the full-FOV non-thermal velocity peaked before the peak of the full-FOV intensity in the case of the intermediate flare (not shown here). On the other hand, in event (c), which can be classified as a thermal-rich flare, the full-FOV non-thermal velocity and the full-FOV intensity peaked simultaneously (not shown here). Therefore, the timing between the full-FOV non-thermal broadening and the full-FOV intensity of the Fe\textsc{xxiv} line shows the same trend as in the other events. In event (e), which can be classified as a thermal-poor flare, the duration of the flare is too short to determine the timing relationship between the intensity and non-thermal broadening from EIS observations, because the temporal resolution of EIS is long.

We study the relationships among the locations of the high-energy electrons, the non-thermal broadening, the flare loop, and the flare ribbon. Figure 12 shows the intensity of the AIA 131 Å data (color image), the non-thermal velocity of EIS data at 192.03 Å (green contours), the intensity of the AIA 1700 Å image (black contours), and the NoRH 17 GHz brightness temperature at the peak of the full-FOV non-thermal velocity.
The non-thermal broadening of Fe xxiv source of the 17 GHz microwaves is located at the footpoint of the 180 km s\(^{-1}\) (red contours). The green contours represent 100, 140, and 180 km s\(^{-1}\) of the maximum brightness temperature. The AIA 131 Å image corresponds to the 10\(^7\) K flare loop and the AIA 1700 Å contour corresponds to the flare ribbons that are the footpoints of the flare loop. It seems that in events (a) and (b), which can be classified as intermediate flares, the non-thermal broadening occurred at the footpoint. The microwave source is located at the top of the flaring loop. On the other hand, in events (c) and (d), which can be classified as thermal-poor flares, it seems that the non-thermal line broadening occurred at the looptop. The microwave source is located at the footpoint of the flare loop. Furthermore, in event (e), which can be classified as a thermal-poor flare, it seems that the non-thermal line broadening occurred at the footpoint. The microwave source is located at the top of the flaring loop. The trend of the temporal evolution of the non-thermal line broadening was also the same as discussed in the previous section (not shown here). All the flares, except for event (e) that has no data after the peak time of the microwave burst, show that the non-thermal broadening is located at the top of the flaring loop after the microwave burst.

4. DISCUSSION

4.1. Summary of the Results

We analyzed the relationship between the location of EUV non-thermal broadening and high-energy particles during large flares mainly using Hinode/EIS observations. We also paid attention to the relationship between the location of the non-thermal broadening and the thermal richness of the flares. We found the following results: (1) the non-thermal broadening of Fe xxiv occurred at the footpoint of the flare loop at the beginning of the intermediate flares, (2) the source of the 17 GHz microwaves is located at the top of the flaring loop at the beginning of the intermediate flares, (3) the non-thermal broadening of Fe xxiv gradually moved toward the looptop after the microwave burst in the case of the intermediate flares, (4) the non-thermal broadening of Fe xxiv occurred at the top of the flaring loop at the beginning of the thermal-rich flares, (5) the source of the 17 GHz microwaves is located at the footpoint of the flare loop at the beginning of the thermal-rich flares, and (6) the non-thermal broadening of Fe xxiv is also located at the top of the flaring loop after the microwave burst in the case of thermal-rich flares. The results are summarized in Table 2.

Table 2
Summary of Observations

| Event | GOES Class | TEI | Impulsive | Non-thermal Broadening | 17 GHz Source |
|-------|------------|-----|-----------|------------------------|--------------|
| (a)   | M1.0       | 0.06| Yes       | Footpoint              | Looptop      |
| (b)   | M1.9       | 0.05| Yes       | Footpoint              | Looptop      |
| (c)   | M4.4       | 0.73| No        | Looptop                | Footpoint    |
| (d)   | M7.4       | 0.58| No        | Looptop                | Footpoint    |
| (e)   | M1.0       | -0.52| Yes      | Footpoint              | Looptop      |

4.2. Non-thermal Broadening at Footpoints and Looptop Sources

Since we have studied the location of the non-thermal broadening based on imaging spectroscopic observations, we are in a better position to discuss the nature of the various sources of non-thermal broadening. As we discussed in Section 1, past observations indicated that the non-thermal broadening might occur at both the looptop and footpoint of a flare loop (e.g., Mariska & McTiernan 1999). Furthermore, Ranns et al. (2001) found that the non-thermal broadening occurs after the HXR burst in the case of the impulsive flares. On the other hand, these authors also found that the non-thermal broadening occurs before the HXR burst in the case of long duration flares. They concluded that the origin of the non-thermal broadening might be evaporation flows at the footpoint of the flare loop in the case of impulsive flares, although the origin of the non-thermal broadening might be turbulence at the top of the flaring loop in the case of long duration flares. We studied the location of the non-thermal broadening in the case of both impulsive and long duration flares. Our results are certainly consistent with previous results from spatially unresolved observations. Furthermore, we found that some of the non-thermal broadening during the impulsive flares was clearly associated with the flare ribbons (Figure 6) and the blueshifted component of Fe xxiv (Figure 5), which is an indication of chromospheric evaporation flows. Evaporation flows associated with non-thermal broadening have been clearly observed at the footpoint of flare loops (e.g., Milligan 2011). The origin of non-thermal broadening is thought to be multiple flow speeds of evaporation, because generally the broadening line profile is highly distorted (e.g., Imada et al. 2008). Therefore, it is plausible that the origin of the non-thermal broadening at the footpoints during intermediate flares is evaporation flows. To investigate the origin of the non-thermal broadening at the looptop in the case of thermal-rich flares, we study the detailed line profile of Fe xxiv. Figure 13 shows the line profile integrated over 15 × 15 arcsec\(^2\) around the peak position of the non-thermal velocity. The + symbols represent the observations and the solid line represents the Gaussian fitting result. The line profile is almost symmetric (at least within the FWHM), although there is an excess in the blue wing. Furthermore, it seems that the location of the non-thermal broadening is above the looptop rather than the top of the flaring loop, where we cannot observe any signatures of evaporation flows (for example, flare ribbons or flows). The non-thermal broadening at the looptop has different characteristics than the non-thermal broadening at the footpoint. Thus, it is plausible that the origin of the non-thermal broadening at the looptop might
Figure 14. Schematic illustration of the difference between thermal-rich flares and other flares. The gray arrow in a circle means the pitch angle distribution of high-energy electrons.

be turbulence/waves produced by the interaction between the reconnection outflow and the bright flare loop.

4.3. Thermal-rich versus Thermal-poor Flares

In our results, the thermal-rich flares have a footpoint source of microwave emission and the other flares have a looptop source of microwave emission. This result is consistent with the discussions in Kawate et al. (2011). These authors claimed that the thermal-rich flares have microwave sources located near footpoints based on the microwave flux increasing from the center to the limb. On the other hand, the looptop microwave source may indicate that the high-energy electrons are trapped at the looptop either by wave scattering or by magnetic mirroring forces.

We describe our interpretation of observational results in Figure 14. The microwave sources are found at the looptop/footpoint of the flares in the case of intermediate/thermal-rich flares, respectively. Furthermore, we observe non-thermal broadening at the footpoint/looptop in the case of intermediate/thermal-rich flares, respectively. We think that the non-thermal broadening may provide clues about the presence of turbulence/waves that play an important role in the pitch angle scattering of high-energy electrons. The pitch angle distribution of high-energy electrons in the case of thermal-rich flares should be isotropic at the looptop. Then, most of the high- and low-energy, electrons can travel along the flare loop and gradually penetrate into the chromosphere because the loss cone is refilled by continuous pitch angle scattering at the looptop during the bouncing motion. On the other hand, in the case of intermediate and thermal-poor flares, only electrons whose pitch angles are inside the loss cone can precipitate into the chromosphere at the beginning of the flares. However, to prove our speculation it is important to know whether or not turbulence can really interact with electrons and play a role in the electron pitch angle scattering. It is thus a critical task in future studies to determine the spatial scale of the turbulence/waves underlying the non-thermal broadening presented in this study.

We thank T. Watanabe, H. Harra, K. Ichimoto, V. Melnikov, and K. Shibata for fruitful discussions.

Hinode is a Japanese mission developed and launched by ISAS/JAXA, collaborating with NAOJ as a domestic partner, and NASA and STFC (UK) as international partners. Scientific operation of the Hinode mission is conducted by the Hinode Science Team organized at ISAS/JAXA. This team mainly consists of scientists from institutes in the partner countries. Support for the post-launch operation is provided by JAXA and NAOJ (Japan), STFC (UK), NASA, ESA, and NSC (Norway).

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