TEMPORAL AND SPATIAL ANALYSES OF SPECTRAL INDICES OF NONTHERMAL EMISSIONS DERIVED FROM HARD X-RAYS AND MICROWAVES

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ABSTRACT

We studied electron spectral indices of nonthermal emissions seen in hard X-rays (HXRs) and microwaves. We analyzed 12 flares observed by the Hard X-Ray Telescope aboard Yohkoh, Nobeyama Radio Polarimeters, and the Nobeyama Radioheliograph (NoRH), and compared the spectral indices derived from total fluxes of HXRs and microwaves. Except for four events, which have very soft HXR spectra suffering from the thermal component, these flares show a gap $\Delta \delta$ between the electron spectral indices derived from HXRs $\delta_X$ and those from microwaves $\delta_{\mu}$ ($\Delta \delta = \delta_X - \delta_{\mu}$) of about 1.6. Furthermore, from the start to the peak times of the HXR bursts, the time profiles of the HXR spectral index $\delta_X$ evolve synchronously with those of the microwave spectral index $\delta_{\mu}$, keeping the constant gap. We also examined the spatially resolved distribution of the microwave spectral index by using NoRH data. The microwave spectral index $\delta_{\mu}$ tends to be larger, which means a softer spectrum, at HXR footpoint sources with stronger magnetic field than that at the loop tops. These results suggest that the electron spectra are bent at around several hundreds of keV, and become harder at the higher energy range that contributes the microwave gyrosynchrotron emission.

Key words: acceleration of particles – Sun: corona – Sun: flares – Sun: radio radiation – Sun: X-rays, gamma rays

1. INTRODUCTION

During the impulsive phase of solar flares, electrons are accelerated up to the energy of MeV, and are responsible for nonthermal emissions with power-law spectra observed in hard X-rays (HXRs) and microwaves. In HXRs the bremsstrahlung emission from electrons with the energy of more than tens of keV is dominant (Brown 1971), while the gyrosynchrotron emission from more than several hundreds of keV electrons is dominant in microwaves (White & Kundu 1992; Bastian et al. 1998; Bastian 1999). HXR and microwave nonthermal emissions are very similar in the light curves (e.g., Kundu 1961; Kai 1986), and therefore it has been generally accepted that they are produced by a common population of accelerated electrons.

The electron spectra derived from HXR emissions are, on the other hand, often different from those derived from microwave emissions. The electron spectral indices of the power-law distribution derived from HXRs $\delta_X$ are, in many cases, larger than those derived from microwaves $\delta_{\mu}$, that is $\delta_X > \delta_{\mu}$ (Kundu 1965; Silva et al. 1997, 2000). According to the study by Silva et al. (1997), the average gap between $\delta_X$ and $\delta_{\mu}$, $\Delta \delta = \delta_X - \delta_{\mu}$ is 0.5–2.0. This means that microwave spectra are harder than the HXR ones, and that acceleration and/or traveling mechanisms could be different for these wavelengths. For example, Melrose & Brown (1976) suggested the so-called trap-plus-precipitation model, in which the magnetic trap works more effectively for such higher energy electrons that emit microwaves than HXR emitting electrons with lower energy. Minoshima et al. (2008), on the other hand, showed in their numerical calculation that the gap $\Delta \delta$ is naturally generated even from the electron distribution with a single power-law spectrum, since microwave and HXR emissions are from different electrons (trapped and precipitating ones, respectively). In the early phase of a flare, however, the magnetic trap is probably not so effective, and we can examine the features of the nonthermal electrons without having to deal with the trapping effect. Moreover, it is crucially important to analyze imaging data both in HXRs and in microwaves, since we can resolve spatially the precipitating (at footpoints) and trapped (at loop tops) components with them.

In this paper, we report the results of the analyses on the electron spectral indices derived from HXRs and microwaves, and also discuss the temporal and spatial characteristics. We used the HXR data obtained with the Hard X-Ray Telescope (HXT; Kosugi et al. 1991) aboard the Yohkoh satellite (Ogawara et al. 1991). The microwave data were taken with the Nobeyama Radio Polarimeters (NoRP; Torii et al. 1979; Shibasaki et al. 1985), and the Nobeyama Radioheliograph (NoRH; Nakajima et al. 1994) at Nobeyama Solar Radio Observatory, National Astronomical Observatory of Japan. These data enable us to examine the nonthermal features of the accelerated electrons spatially, temporally, and spectroscopically both in HXRs and in microwaves. In Sections 2 and 3 we summarize the observations and the method of the analyses, respectively, and we show the results of the statistical analyses in Section 4. In Section 5 we present discussions and our conclusions.

2. OBSERVATIONS

We used HXR data obtained with Yohkoh/HXT. By using the HXT data, we can synthesize the HXR images in four energy bands, namely the $L$ band (14–23 keV), $M$ 1 band (23–33 keV),
M2 band (33–53 keV), and H band (53–93 keV). The spatial and temporal resolutions of the HXT images are 5′ and 0.5 s, respectively. To obtain the HXR photon spectral index \( \gamma \) (\( I_X(\epsilon) \propto \epsilon^{-\gamma} \)), where \( I_X \) is the HXR intensity, and \( \epsilon \) is energy of the photon), we used the data in the two highest energy bands, i.e., the HXT M2 and H bands, because HXR emissions with energy less than 30 keV sometimes suffer from the contribution of the thermal emissions. Therefore, the HXR photon spectral index \( \gamma \) is roughly written as:

\[
\frac{\log(F_{\nu,pk})}{\log(\epsilon_H)} = \frac{\log(\epsilon_M)}{\log(\epsilon_H)} - \gamma,
\]

where \( \epsilon_M \) and \( \epsilon_H \) are the effective energies for the M2 and H bands. However, as we will discuss later, some events showed the effects of the superhot thermal components even in the M2 band. In this work we calculated the HXR photon spectral indices by using the programs hxt Powerlaw in the Solar SoftWare (SSW) package on IDL. We accumulated the HXT data for two seconds in the spectral analyses to reduce the photon noise.

We also used the HXR spectra derived from the Wide Band Spectrometer (WBS; Yoshimori et al. 1991). The Hard X-Ray Spectrometer (HXS), one of the sensors installed on the WBS, is dedicated to taking HXR spectra over a wide energy range. WBS/HXS can obtain HXR spectra with higher spectral resolution than HXT, although it cannot obtain the spatial information. Therefore, the data of WBS/HXS and HXT are complementary for the imaging spectroscopy in HXRs. Sato et al. (2006) summarized all the events observed by WBS, and we used their database of the HXR spectra.

In microwaves the gyrosynchrotron emission is dominant during the impulsive phase of a flare. The spectrum in the microwave range \( F_\nu \) is approximately fitted with the two power-law indices \( \alpha_M \) and \( \alpha_H \) by the function as follows:

\[
F_\nu = F_{\nu, pk} \left( \frac{\nu}{\nu_{\text{pk}}} \right)^{\alpha_M} \left\{ 1 - \exp \left[ - \left( \frac{\nu}{\nu_{\text{pk}}} \right)^{\alpha_H - \alpha_M} \right] \right\}
\approx \begin{cases} 
F_{\nu, pk} \left( \frac{\nu}{\nu_{\text{pk}}} \right)^{\alpha_M} & \text{for } \nu \ll \nu_{\text{pk}} \\
F_{\nu, pk} \left( \frac{\nu}{\nu_{\text{pk}}} \right)^{\alpha_H} & \text{for } \nu \gg \nu_{\text{pk}}.
\end{cases}
\] (1)

The optically thin part, therefore, follows the power law distribution with a negative spectral index \( \alpha \) (=\( \alpha_H \)) as \( F_\nu \propto \nu^{\alpha} \), where \( F_\nu \) is the flux density at frequency \( \nu \) (e.g., Ramaty 1969; Dulk 1985).

In this study we used the microwave data taken with NoRP, which measures the total fluxes at 1, 2, 3.75, 9.4, 17, 35, and 80 GHz, with a temporal resolution of 0.1 s. By fitting a NoRP spectrum with Equation (1), we can obtain the spectral index \( \alpha_H \) of the optically thin gyrosynchrotron. We did not use the NoRP 80 GHz data in this work due to the poor statistics. For some events, the NoRP 1 GHz data were also ruled out, because they clearly did not follow the gyrosynchrotron, but rather the plasma emission. We accumulated the NoRP data for 5 s to reduce the noise level. The microwave fluxes of the NoRP data are determined with the error of less than 10% of the signal for 1, 2, 4, 9.4 GHz, and 15% for 17 and 35 GHz, which is mainly due to the observation conditions such as the calibration and the weather. The error in determining \( \alpha_H \) is also affected by the accuracy of fitting, and is finally estimated to be about \( \pm 0.5 \).

NoRH also observes the Sun at 17 and 34 GHz. The microwave two-dimensional images are synthesized from the NoRH data, and the spatial resolutions (FWHMs of the synthesized beam) of about 14″ for 17 GHz and 7″ for 34 GHz. The time cadence of the data we used in this work is one second. We can derive the two-dimensional distribution (map) of the microwave spectral indices using the NoRH data (\( \alpha_H \)), by calculating log(\( F_{34 \text{GHz}}/F_{17 \text{GHz}} \))\( \log(34 \text{GHz}/17 \text{GHz}) \)^{-1} for each position of images. If we assume that the turnover frequency is less than 17 GHz, the derived \( \alpha_H \) is for the optically thin gyrosynchrotron emission.

Here, we have to note the calibration of the NoRH 17 and 34 GHz data. NoRH calibrates phase and gain by using the Sun itself (i.e., the solar disk) as a calibrator, thanks to the redundant antenna configuration. However, the fundamental (smallest) spacing of the antennas (=1.5 m) corresponds to the maximum wavelength in the space of 20′ (=1200″) at 34 GHz, which means that the whole solar disk is not resolved. The solar disk at 34 GHz is partially overlapped with other fake solar disk images, and therefore the background (quiet) solar disk is possibly not well determined. To correct this, we adjusted the flux of the flare region taken by NoRH 34 GHz, which is subtracted by the preflare data, to the fitting results derived from NoRP. NoRP calibrates those fluxes by using sky and absorber levels. In our cases the NoRH 34 GHz fluxes are usually smaller than the NoRP 35 GHz ones, and the ratio (NoRH 34 GHz)/(NoRP 35 GHz) is from 0.4 to 1.2. This calibration possibly reduces the derived spectral index \( \alpha_H \) by about −1.0 at a maximum. We also corrected the NoRH 17 GHz flux of the flare region, by using the fitting result from NoRP. Although the correction ratio (NoRH 17 GHz)/(NoRP 17 GHz) ranges from 0.6 to 1.2, it is roughly comparable to 1 in most cases. This calibration causes the error on \( \alpha_H \), mainly due to the measurement error of the radio flux by NoRP, and is about 0.4. The relative displacement between the images in 17 GHz and those in the 34 GHz due to the NoRH image syntheses also causes the error to estimate the spectral index \( \alpha_H \). The NoRH image syntheses hold an uncertainty on the positioning of about 5″, and in this case the error on \( \alpha_H \) is about \( \pm 0.2 \) for bright emission sources.

3. DATA ANALYSES

Strong (i.e., intense) and large events are preferable for our imaging spectroscopic analyses. Therefore, we sought solar flares observed by HXT, NoRH, and NoRP for the period from the start of the dual-frequency observation with NoRH (November 1995) to the end of the observation of Yohkoh (December 2001), and selected 12 flare events that meet the following criteria. (1) The flare is larger than M1.0 on the GOES scale. (2) The flare is an event listed in The Yohkoh HXT/SXT Flare Catalogue (Sato et al. 2003). and the maximum HXR intensity is so strong that the counts per second per subcollimator in the HXT M2 band are larger than 30. (3) The spatial size of the microwave emission source observed with NoRH at 17 GHz is large enough, and it is more than four times the beam size. (4) The microwave images can be successfully synthesized from the NoRH data, in other words, the microwave emissions are not extremely strong. (5) The optically thin parts of the gyrosynchrotron emission are well defined from the NoRP data, which means that the turnover frequencies determined from the fitting do not reach 17 GHz or more. (6) The peak time of the event is between 00:00 UT and 06:00 UT, which corresponds to 09:00 and 15:00 JST (i.e., Japanese daytime), and the NoRH beam pattern is not so distorted. Table 1 lists all the 12 flares. Figure 1 also shows temporal and spatial features of each event. The selected events are widely distributed longitudinally and in the flare size.

9 The normal tool for synthesizing NoRH images often fails in the case of very strong microwave emission.
Figure 1. Time profiles and images for each selected event. The intensity (top) and spectral (bottom) time profiles are shown on the left-hand side of each sub-figure. The HXR and microwave light curves are taken by the HXT M2 band (33–53 keV) and the NoRP 17 GHz, respectively. The microwave and HXR spectral time profiles are plotted with the square (□) and cross (+), respectively. The 17 GHz contour images obtained by NoRH and the HXR ones obtained with HXT (M2 band) are shown in the top right panel of each sub-figure by the black and gray lines, respectively. The contour levels of the microwave and HXR images are 20%, 40%, 60%, 80%, and 95% of the peak intensity.
3.1. HXR Spectral Indices

In the selected events we confirmed that the dominant HXR emissions are from footpoints of flare loops, and no loop top HXR sources are included, such as those reported by Masuda et al. (1994). This means that they are produced by bremsstrahlung caused by the interactions between the precipitating energetic electrons and the dense chromospheric plasma. Therefore, it is reasonable that we adopt the thick-target model (Brown 1971; Hudson et al. 1978; Sakao 1994) for the HXR emission sources. In this paper we determined the spectral indices $\gamma$ from the total HXR intensities, assuming that the HXR
emissions from the footpoint sources are so strong that we can approximately equate the total intensities to the emissions from the footpoint source.

The thick-target model suggests the relation between $\gamma$ and the spectral index $\delta_X$ of the number flux of the injected energetic electrons $F_N(E) = \frac{dN(E)}{dt} \propto E^{-\delta_X}$, as $\delta_X = \gamma + 1.0$. To estimate the spectral index $\delta_X$ of the accelerated electrons $N(E)$, we further have to consider the traveling time of the electrons $\tau N(E) \approx F_N(E) \tau \propto E^{-\delta_X}$, since energy-dependent $\tau$ moderates the spectral index and $\delta_X \neq \delta_X$. In this paper we adopted the typical timescale over which the precipitating electrons travel the effective length $L$ in the flare loops with the velocity $v$, that is, $\tau = L/v$. The traveling time is proportional to $v^{-1}$, that is, $\tau \propto E^{-0.5}$. Then, the electron spectral index derived from the HXR emissions $\delta_X$ follows the relation $\delta_X = \gamma + 1.5$.

The seventh column of Table 1 shows the derived spectral index $\delta_X$ at a time when the HXR emission records the maximum in the HXT M2 band for each event as shown in the second column. The derived $\delta_X$ ranges from 3.8 to 6.6. The error to estimate the spectral index $\gamma$ is about $\pm 0.5$, and the same is true for $\delta_X$, under the assumption of single power-law HXR spectra. The photon noise is the main factor of the error, and therefore it is even reduced during strong HXR emissions (to about $\pm 0.2$).

As shown in Figure 1, in most cases, the temporal variations of the spectral index, which are plotted with the cross mark (+), show the soft–hard–soft (SHS) behavior at the peak times of the HXR emissions. Therefore, $\delta_X$ recorded in Table 1 is roughly the minimum value during the burst. As we describe below, for the 2000 January 12 (event b) and the 2000 March 3 (event f) flares, we chose other sub-peaks instead of the maximal intensities, because we could not well fit the microwave spectra.

In Figure 2 we show the HXR spectra derived from WBS/HXS. These are from the database of Sato et al. (2006). The times on the top are the integration time in UT, and they almost cover the HXR maxima. The solid lines are the power-law distribution of the HXR spectra derived from HXT, while the absolute values are arbitrary. For the 2000 March 3 (event f) and the 2001 March 30 (event k) flares, the integration times of WBS/HXS are out of the HXT peak times we took. We can confirm that the HXR spectral indices derived from HXT fit the HXR spectra of WBS/HXS within the margin of errors as small as $\pm 0.2$ (Sato et al. 2006).

### 3.2. Microwave Spectral Indices

Next, we derived the spectral indices of the accelerated electrons $\delta_\mu$ from the microwave emissions taken with NoRP. For the optically thin gyrosynchrotron emission, $\alpha$ is related to the spectral index of the accelerated electrons $\delta_\mu$. There have been several studies to derive the relation between $\delta_\mu$ and $\alpha$, and we adopt the approximation derived by Dulk (1985) here, and $\delta_\mu = (1.22 - \alpha)/0.9$. In this paper, we distinguish the spectral index derived from NoRP $\delta_\mu$ from that from NoRH $\delta_\mu$ with the subscripts $P$ and $H$. Figure 3 shows some examples of the NoRP spectra and the fitting result at the time of HXR maximal intensity (column 2). The eighth column of Table 1 also shows the spectral index derived from NoRP $\delta_\mu$ at the time of the HXR maxim. As we mentioned above (Section 2), the error to determine $\alpha_P$ is about $\pm 0.5$, and therefore that for $\delta_\mu_P$ is about $\pm 0.6$. We confirmed that the contribution from the free–free emission at 35 GHz is negligible. The temporal variations of the $\delta_\mu$ follow the gradual-hardening (GH) or soft–hard–harder (SHH) behaviors as shown in Figure 1. We added the gap between the spectral index derived from HXR and that from microwaves $\Delta \delta = \delta_X - \delta_\mu$ in the ninth column. We will discuss $\Delta \delta$ in more detail later.

For the 2000 January 12 and 2000 March 3 flares (events b and f, respectively), the turnover frequencies are higher than 20 GHz at the HXT maxima, and we could not well fit the spectral indices $\alpha$ for the optically thin part of the gyrosynchrotron emission. Therefore, we chose other sub-peaks of the HXR light curves of these events for the spectral analysis. These peak times are shown with gray vertical lines in Figure 1.

From the NoRH data, we can derive the spatially resolved spectral indices $\alpha_H$ (and therefore $\delta_\mu_H$). We can compare, for
example, $\delta_{\mu P}$ at the footpoint sources with that of the loop-top ones. As we just mentioned, we confirmed that the turnover frequencies derived from NoRP are sufficiently lower than 17 GHz except for the peak times of the events (b) and (f). For the two events, we again selected preceding sub-peaks for further spectral analyses. Therefore, the indices $\alpha_H$ derived from only two frequencies (17 and 34 GHz) are mainly for the optically thin gyrosynchrotron, while we cannot rule out the possibility that they are locally enhanced to be close to or larger than 17 GHz. Figure 1 shows such two-dimensional distribution of the index $\alpha_H$, which we call “$\alpha$-map” in the bottom right sub-figure.

4. RESULTS

Table 1 lists the selected 12 events, with the peak time of the HXT $M_2$ band (column 2), the delay of the peak times of microwave (NoRP 17 GHz) compared to those of HXR (HXT $M_2$ band) in second (column 3), the spectral index derived from HXT $\delta_X$ (column 7), that derived from NoRP $\delta_{\mu P}$ (column 8), and the gap $\Delta \delta (= \delta_X - \delta_{\mu P})$ (column 9). In Figure 1 we present the time profiles of the HXR flux of HXT $M_2$ band and the microwave flux at 17 GHz taken with NoRP (top left). The time profiles of the spectral indices $\delta_X$ and $\delta_{\mu P}$ are also shown with the cross (+) and square (□) signs, respectively, in the bottom left sub-figure. We also present the contour images in the microwave taken with NoRH at 17 GHz (top right) of the selected events. The contour levels of the microwave images are 20%, 40%, 60%, 80%, and 95% of the peak intensity. The microwave images are overlaid with the HXR contour images taken with HXT $M_2$ band with the contour levels of 20%, 40%, 60%, 80%, and 95% of the peak intensities.

4.1. Peak Delay of Microwave Emissions

As the top left sub-figures of Figure 1 show, the microwave peaks almost always lag behind the HXR peaks. The delay times for the events are listed in the third column of Table 1. These delays of microwave peaks from HXR ones have often been observed, and reported by various authors (e.g., Güdel
et al. 1991). In the current case the delays are from 0 to 21 s, and the average is 7.3 s. These are comparable with the result by Nakajima et al. (1985a). Delays of microwave peaks from HXT ones are thought to be caused by magnetic trapping for microwave-emitting electrons, while HXR emissions are from the electrons directly precipitated to the chromosphere.

4.2. Gap of Spectral Indices $\Delta \delta$

According to the results summarized in Figure 1 and Table 1, especially concerning the gap $\Delta \delta$, we first categorize these events into two groups. As we mentioned above, the temporal variations of $\delta_X$ clearly show the SHS behavior at the peaks, while those of $\delta_{\mu P}$ show hardening features (GH or SHH) as flares progress. In most cases, therefore, the listed gap $\Delta \delta$ is the smallest value near the HXR peaks. For all events, the gap $\Delta \delta$ is always positive, which means that the electron spectra derived from microwaves of this group are always harder than those from HXRs.

The first is the group with smaller gap ($\Delta \delta < 2.2$). This group shows the electron spectral index derived from HXRs $\delta_X$ of about $4.6 \pm 0.8$, while that derived from microwaves $\delta_{\mu P}$ is about $3.0 \pm 0.8$. The gap $\Delta \delta$ of about 1.6 is well consistent with the result by Silva et al. (2000). Eight events (from a to h) belong to this group. The other 4 events (from i to l), which belong to the second group, have much larger gaps $\Delta \delta$ of greater than 2.7. In particular, the electron spectral index derived from HXRs $\delta_X$ is much larger than those of the first group, and is about $6.2 \pm 0.5$. We checked the HXT data for those events, and concluded that the HXR emissions suffered from the thermal components even in the M2 band. The HXR spectra derived from WBS/HXS (Figure 2) are also very soft. Huang et al. (2006) studied one of them (the 1998 November 28 flare; event i), in more detail, and concluded that there is a vast super-hot thermal component in this flare, which softens the HXR spectrum. Henceforth, we discuss only the first group.

Even after we eliminate the second group, there remains the gap $\Delta \delta$. Figure 4 shows the scatter plot with the horizontal axis of $\delta_X$ and the vertical axis of $\delta_{\mu P}$. The events are marked by the asterisks (*). The solid line shows the points where $\delta_X$ is equal to $\delta_{\mu P}$. This also suggests that there is a certain gap between the spectral indices $\Delta \delta$.

4.3. Microwave Emission Sources

As shown in Figure 1, the sites of the dominant microwave emissions are different for each event. According to the spatial displacement between the brightest position of the microwave emission sources and those of the HXR sources, and/or by using imaging observations in soft X-rays and extreme ultraviolet, we categorized the microwave emission sources into two cases: footpoint source (group F; displacement is less than $5^\circ$) and loop source (group L; displacement is larger than $5^\circ$) as noted in the sixth column of Table 1. Here, we note that the brightest microwave emission source seen in the 2000 November 25 flare (event g) is confirmed to be a footpoint source (Takasaki et al. 2007), although it is displaced from the HXR source by about $40^\circ$. Therefore, we categorized this case as a footpoint event.

We confirmed that the dominant microwave emission sources appear at the tops or legs of flare loops for many cases (5 of 8 events). This is consistent with the result of Huang & Nakajima (2009) or Melnikov et al. (2002). We will discuss the difference between the temporal evolution of the spectral indices for group L and that for group F in the next subsection.

![Figure 4](image-url) Scatter plot between the electron spectral index derived from microwaves $\delta_{\mu P}$ (horizontal axis) and that from HXRs $\delta_X$ (vertical axis). The solid line shows the points where $\delta_X$ corresponds to $\delta_{\mu P}$ ($\Delta \delta = 0$). Only the small gap events ($\Delta \delta < 2.2$, see the text) are plotted.

4.4. Temporal Evolution of Spectral Indices

We examine the temporal evolution of the spectral indices. The HXR spectral index $\delta_X$ mostly shows the SHS behaviors at each short peak, while two of them (events f and g) show even GH features. The temporal evolution of the microwave spectral index $\delta_{\mu P}$, on the other hand, seems different, according to the position of microwave emission sources (i.e., group L/F).

For group L (events a, b, c, d, and e), the time profiles of the spectral indices ($\delta_{\mu P}$ and $\delta_X$) show similar evolution from start to peak of the bursts, while the gap $\Delta \delta$ increases with time after the peaks. In other words, the electron spectral index derived from HXRs $\delta_X$ increases after the peaks, showing the SHS features, while the electron spectral index from microwaves $\delta_{\mu P}$ becomes even smaller showing SHH or GH features. For group F (events f, g, and h), on the other hand, both the spectral indices ($\delta_{\mu P}$ and $\delta_X$) show similar evolution through the impulsive phase while maintaining a gap of about 1.6. However, event h is different from the other two events of group F. This event shows the SHS features both in the microwave index $\delta_{\mu P}$ and in the HXR index $\delta_X$, while the others show GH features.

From the point of the temporal evolution, we can, therefore, reclassify the eight events into three groups: (L) microwave emission sources are located at loop tops/legs, and $\delta_X$ and $\delta_{\mu P}$ show SHS and GH features, respectively (events a, b, c, d, and e), (F) microwave emission sources are from footpoints, and both $\delta_X$ and $\delta_{\mu P}$ show GH features (events f and g), (F*) microwave emission source is again from footpoints, but both $\delta_X$ and $\delta_{\mu P}$ show SHS features (event h).

Figure 5 is roughly a realignment of Figure 1, but focuses much more on the temporal evolution of the microwave spectral index $\delta_{\mu P}$ during the bursts for the groups L (top) and F (bottom). The vertical dotted lines correspond to the times when the
microwave 17 GHz fluxes taken by NoRP exceed 100 SFU (Solar Flux Units). We determine this time as the start of the bursts. The vertical dashed lines correspond to the times when the 17 GHz fluxes become half of the peak values. We define this time as the end of the bursts. Although even after the end times the microwave indices \( \delta_{\mu} \) become smaller, the fluxes probably suffer from the thermal component in the microwave emissions, which should be avoided in the analysis. For the 2000 November 25 flare (event g), we defined the end time just after the peak HXR time, since the hardening seems saturated after 01:12 UT, and no further hardening is seen. The bottom panels again show the time profiles of the spectral index \( \delta_{\mu} \) with the square (□) marks. The overlaid time profiles are the spectral index \( \delta_{X} \) (cross +). We subtracted 1.5 from the original value of the index to clearly show the temporal variation. The numbers noted in the figure show how much the spectral indices \( \delta_{\mu} \) decrease between the two vertical dotted lines. We also summarized the hardening degree in the tenth column of Table 1. As a result, the nonthermal spectra harden with the indices of 1.0 on the average. The hardening with the microwave spectral index of about 1 seems to be consistent with the discussion of the trapping time of relativistic electrons (Bai & Ramaty 1979; Petrosian 1985).

From the start to the peak of the HXR bursts, which corresponds to the time range from the dotted line to the thick gray line in Figure 5, both the time profile of the microwave spectral index \( \delta_{\mu} \) and that of the HXR spectral index \( \delta_{X} \) decrease simultaneously, keeping a certain gap \( \Delta \delta \) of about 1.5. The 2000 November 25 flare (event g) is a special case due to the very long duration and the smooth variation of the HXR and microwave emissions (Takasaki et al. 2007). This flare shows GH features even in the HXR spectral evolution, and is typical of “type-C flares” (e.g., Hoyng et al. 1976), which have been discussed from the Hinotori era (Cliver et al. 1986; K a i 1986; Dennis 1985; Kosugi et al. 1988). These imply that the magnetic trap effectively works both on the microwave-emitting electrons and even on the HXR-emitting electrons. The HXR-emitting electrons are trapped in the magnetic loop at least once before they...
precipitate into the chromosphere. The dominant microwave emission source is located at the footpoint conjugated with the HXR source, which means that these microwave-emitting electrons escape from the magnetic trap. As Takasaki et al. (2007) reported, on the other hand, the microwave footpoint emission source disappears and the dominant emission source is from the loop top during the valley times. Therefore, the gaps $\Delta \delta$ increase during the valley times.

4.5. Spatial Features of Spectral Index $\delta_{\mu}$

The difference between the microwave emission sources and the HXR emission sources implies that the microwave emissions mainly come from electrons trapped magnetically within the flare loop that connects the HXR footpoint sources. Spatially resolved analyses on the spectral indices are, therefore, required for these events to explain the reason for the certain gap $\Delta \delta$ of about 1.6 confirmed in the current study. By using the NoRH data, we examine the spatial distribution of the spectral indices derived from microwaves, and compare the value at the footpoint ($\delta_{\mu,H}(X)$) with that at the loop top ($\delta_{\mu,P}(X)$).

First, we derived the electron spectral index from NoRH microwave emission $\delta_{\mu,H}$ at the brightest emission positions. The brightest regions are determined to be regions where the intensities at 17 GHz are larger than 80% of the maximum intensities, and the derived spectral index is noted as $\delta_{\mu,H}(\mu)$. For many cases in our results, the dominant microwave emissions are from loop tops (or legs), and $\delta_{\mu,H}(\mu)$ show the values there. The twelfth column of Table 1 presents the list of $\delta_{\mu,H}(\mu)$. These items roughly correspond to those derived from the total intensity $\delta_{\mu,P}$ (column 8) with the displacement of about 0.5. The displacement is probably due to the spatial distribution of the spectral index. For the 2000 October 29 flare (event e), we failed to correctly derive the $\alpha$-map, because of a large displacement between the position of the NoRH 17 GHz emission source and that at NoRH 34 GHz. The displacement is as large as 10°. Although the reason is unknown, it may be caused by other energy release processes that occurred in the preflare phase. We omitted this event from the further discussions.

Second, we determined the spectral index at the HXR footpoints, that is, $\delta_{\mu,H}(X)$ from the NoRH $\alpha$-map. If there are two HXR footpoint sources, we calculated them separately. For events (f) and (h), we could not, however, correctly derive the spectral index. This is because the HXR footpoint positions are too close to the loop top/leg microwave emission sources, and they are not spatially resolved. For events (a) and (b), one of the two footpoints is too close to the microwave emission source. We showed the spectral indices $\delta_{\mu,H}(X)$ for these footpoint sources in parentheses in the eleventh column of Table 1. The number I/II is the same as that marked for the HXR footpoints in Figure 1. Here we have to note the error of $\delta_{\mu,H}(X)$. The microwave emission from footpoints is weaker than that from loop tops/legs for most cases, and therefore the error to estimate the spectral index $\delta_{\mu,H}(X)$ could be larger than that for the loop top one ($\delta_{\mu,P}(\mu)$). We roughly expect the error to be about $\pm 0.7$. Except for the 2000 April 8 flare (event c), we found the relation that the spectral indices for footpoint sources are larger, which corresponds to the softer spectra, than those at the loop tops/legs, that is, $\delta_{\mu,H}(X) > \delta_{\mu,P}(\mu)$. Especially, in events (d) and (g), $\delta_{\mu,H}(X)$ is quite close to the $\delta_{\mu,P}(\mu)$. We will discuss the spatial features of the spectral index $\delta_{\mu,H}$ and the relation with the magnetic field in the next section.

5. DISCUSSION AND CONCLUSIONS

We examined the electron spectral indices of nonthermal emissions seen in HXRs ($\delta_X$) and microwaves ($\delta_{\mu}$) for 12 flares observed by Yohkoh/HXT NoRP, and NoRH. Eight flares of the selected 12 events show gaps between the spectral indices, i.e., $\Delta \delta$ of about 1.6. The gaps are consistent with the result of Silva et al. (2000). The other four events show larger gaps $\Delta \delta > 2.7$, since they suffer from softening of the HXR spectra (i.e., enlarging the HXR spectral index $\delta_X$) due to the superhot thermal component even in the HXT M2 band. In spite of the fact that we examined the spectral features for the impulsive phase to avoid the effect of magnetic trapping, there still remains a certain gap. On the other hand, from the start to the peak of the HXR bursts (that corresponds to the first vertical dotted line to the thick gray line in Figure 5), both the time profile of the microwave spectral index $\delta_{\mu,P}$ and that of the HXR spectral index $\delta_X$ decrease simultaneously, keeping a certain gap $\Delta \delta$ of about 1.6.

We also investigated the positions of the emission sources by using the HXT and NoRH data. For five of the eight events, the brightest microwave emission sources are located on the loop tops (or legs; group L). On the other hand, for the other three events, they are different from the HXR emission sources, which are mainly from footpoints (group F/P). This implies that the microwave emissions mainly come from electrons trapped magnetically within the flare loop that connects the HXR footpoint sources. The difference in the site of the emission sources possibly causes the gap of the spectral indices $\Delta \delta$. The spatial distribution of the microwave spectral index derived from NoRH $\delta_{\mu,H}$ should therefore be examined. Except for one event (event c), we confirmed that the microwave spectra for footpoint sources are softer than those at the loop tops/legs, that is, $\delta_{\mu,H}(X) > \delta_{\mu,P}(\mu)$. However, the spatial distribution of the microwave spectral index again cannot resolve the gap $\Delta \delta$ even at the sites of the HXR emission sources.

From these results, we concluded that the spectra of the accelerated electrons have a bend, and become harder above several hundreds of keV. This is also consistent with results of previous studies (Yoshimori et al. 1985; Dennis 1988; Matsumoto et al. 2005). Minoshima et al. (2008) numerically calculated the spectral indices of microwave and HXR emissions from the trapped and precipitating electrons, and showed that a softer HXR spectrum and a hard microwave spectrum can be generated. The difference of the spectral indices $\Delta \delta \sim 1.5$, is consistent with our result. However, we showed that the spatially resolved distribution of the microwave spectral index in our study cannot resolve the gap $\Delta \delta$ even at the footpoint sources. This means that there still remains a certain gap $\Delta \delta$.

Here, we examine events (c) and (d) in more detail. Figure 6 shows the photospheric magnetograms for these events obtained by the Michelson Doppler Imager (Scherrer et al. 1995) aboard the Solar and Heliospheric Observatory (Domingo et al. 1995). The levels of the contours are ±400, ±600, and ±800 G with the red and blue lines for positive and negative magnetic polarities, respectively. We overlaid the microwave contour image of NoRH 17 GHz on each panel with light blue lines. The HXR contour image observed with HXT in the M2 band is also overlaid with green lines. The levels of these contours for both contour images are 40%, 60%, 80%, and 95% of the maximum intensities. From Figure 6, we clearly see weak magnetic field strength at HXR footpoints in event (c) of about 250–300 G, while there is quite a strong magnetic field in event (d) of
about 900–1000 G. In event (d), therefore, we expect strong magnetic field for microwave footpoint position, and it could be several 100 G. The microwave gyrosynchrotron emission is strongly related to the magnetic field strength, and only high-energy electrons can contribute under the condition of weak magnetic field strength. On the other hand, with strong magnetic field, weaker energy electrons can contribute the emission. As Bastian (1999) calculated, electrons with the energy of about 500 keV contribute at 500 G, while the energy must be higher than 1 MeV at 200 G to generate 17 GHz emission. This means that low energy electrons with the energy of about several 100 keV emit the gyrosynchrotron at the footpoints. The energy of several 100 keV is as low as that for electrons emitting HXR bremsstrahlung, which causes a very soft spectrum that has the same spectral index \( \delta_M \) as \( \delta_X \). The magnetic field strength at the loop top must be much smaller, and the microwave-emitting electrons have high enough energy of about several MeV, at which the harder spectral component appears. On the other hand, in event (c), the magnetic field strength is weak even at the HXR footpoint sources. This means that high-energy electrons are responsible for the microwave emission even at the footpoint, which corresponds to the observed harder spectral component. From these results, we concluded that the bend of the electron spectra seems to be at about several 100 keV, which is consistent with the previous suggestions (Yoshimori et al. 1985; Dennis 1988). In Figure 3, we cannot see the clear bend of the HXR spectra derived from WBS/HXS, and therefore the bend of HXR spectra in the current case occurs at an energy higher than 300 keV.

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Facilities: NoRH, NoRP, Yohkoh

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Figure 6. Magnetic field strengths for events (c) and (d). The levels of the contours are 400, 600, and 800 G with the red and blue lines for positive and negative magnetic polarities, respectively. The microwave contour image of NoRH 17 GHz on each panel is overlaid with the light blue lines. The HXR contour image observed with HXT in the M2 band is also overlaid with the green lines. The levels of these contours for both images are 40%, 60%, 80%, and 95% of the maximum intensities.
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