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MICROWAVE AND HARD X-RAY SPECTRAL EVOLUTION IN TWO SOLAR FLARES

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ABSTRACT

We explore the time evolution of microwave and hard X-ray spectral indices in two solar flares observed by the Nobeyama Radio Polarimeters (NoRP) and *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*) on 2004 May 21 and November 3. The microwave spectral index, γ_{MW}, is derived from the emission at two frequency channels of 17 and 35 GHz, and the hard X-ray spectral index, γ_{HXR}, is derived from *RHESSI* spectra. These two events follow a soft-hard-harder spectral behavior in the rise-peak-decay phases. Although the microwave and hard X-ray emission are produced by electrons at very different energies, a correlation between their spectral indices is found, indicating a common acceleration mechanism.

Subject headings: Sun: flares — Sun: radio radiation — Sun: X-rays, gamma rays

1. INTRODUCTION

Solar flares are thought to be effective engines for accelerating nonthermal electrons to high energies. When the accelerated electrons propagate along lines of magnetic field toward the photosphere, they interact with the surrounding atmosphere and emit hard X-ray bremsstrahlung and gyrosynchrotron microwave radiation as they lose energy via Coulomb collisions in the lower atmosphere (e.g., Dennis & Schwartz 1989). Observational evidence has been found to support the idea that microwave and hard X-ray emission are produced by nonthermal electrons in the lower solar atmosphere layer during flare eruption (e.g., Takakara & Kai 1966; Kiplinger et al. 1983; Nakajima et al. 1983; Gary 1985; Schmahl et al. 1985; Aschwanden et al. 1990; Aschwanden 1998; Bastian et al. 1998; Asai et al. 2001). One way to derive physical information about these nonthermal electrons is to study the spectral behavior of microwave and hard X-ray emission, since the spectral index can provide the most direct avenue for determining the distribution of nonthermal electrons and their energies.

Considerably more progress has been made in the study of hard X-ray than for microwave spectra. It was recognized early that the hardness of the hard X-ray spectrum changes with time, and that there is a direct correlation between the hard X-ray flux and spectral indices, with a negative power-law dependence between them (e.g., Grigis & Benz 2004). This implies that flares should follow a soft-hard-soft (SHS) spectral behavior in the rise-peak-decay phases (Parks & Winckler 1969; Kane & Anderson 1970; Benz 1977; Dennis et al. 1981; Brown & Loran 1985; Dennis 1985; Fletcher & Hudson 2002; Grigis & Benz 2004). That can be clearly seen in impulsive flares. Using the *RHESSI* data, Grigis & Benz (2004) found that the spectral SHS behavior is observable not only in the general evolution of an impulsive flare, but also in its subpeaks. However, some flares were also observed to monotonically decrease their hardness with time, in a soft-hard-harder (SHH) pattern (Frost & Dennis 1971; Cliver et al. 1986; Kiplinger 1995). These are the so-called gradual-hard flares. Previous observations have shown that the impulsive flares are dominant, or at least more frequent than gradual-hard events (e.g., Kosugi et al. 1988).

Microwave emission from solar flares generally displays the same spectral behavior patterns as hard X-rays. Benz (1984) reported that the microwave spectrum of an individual flare follows a soft-hard-soft behavior. Melnikov & Magun (1998) studied 23 microwave flares and found that all of them display a SHH pattern. Working from Nobeyama Radio Polarimeters (NoRP; Nakajima et al.1985) observations, Ning & Ding (2007) statistically studied the time evolution of microwave spectral hardness, and also found the SHS and SHH patterns.

Microwave and hard X-ray emissions are produced by electrons at very different energies, i.e., from hundreds of keV to several MeV for microwave emission, and from tens to hundreds of keV for hard X-ray emission. Studying the time evolution of the microwave and hard X-ray indices after onset of a flare is one way to derive information about nonthermal electrons with various energies. Up to now, however, a good comparison of their spectral indices has been lacking. In this Letter, we study the microwave and hard X-ray spectral evolution of two flares and quantify the dependence between them.

2. OBSERVATIONS AND MEASUREMENTS

The microwave data that we use here is from the NoRP, which can observe at seven discrete frequency channels (1, 2, 3.75, 9.4, 17, 35, and 80 GHz), with a time resolution of 0.1 s. The microwave spectral index of nonthermal electrons, $\gamma(t)$, is derived from the flux spectral index, $\delta(t)$, by the relation $\gamma(t) = -1.1[\delta(t) - 1.2]$. The $\delta(t)$ index can be computed if we assume a flux frequency dependence of the form $S(\nu, t) = F_0 \nu^{\delta(t)}$ [where $S(\nu, t)$ is the microwave radio flux (sfu), and ν is the frequency] in the optically thin part, i.e., above the turnover frequency f_{max} (e.g., Castelli & Guidice 1976; Melnikov & Magun 1998). The detected f_{max} is 9.4 GHz for these two events. Because we have a small number of discrete frequencies for analyzing microwave indices, it is possible that the detected f_{max} is not the real turnover frequency of the microwave spectrum, which in turn may strongly affect the spectral index fitting result (e.g., Melnikov & Magun 1998). In this Letter, we derive the microwave index using only two channels, 17 and 35 GHz. The 80 GHz channel is not used for spectral fitting due to noise. Figure 1 shows the microwave spectra at four discrete times for the 2004 May 21 flare. In order to increase the signal-to-noise ratio (S/N), it is better to integrate the flux with respect to time (10 s in this Letter) before doing microwave spectral fitting.

The X-ray spectral hardness is derived from data observed by the *Reuven Ramaty High-Energy Solar Spectroscopic Imager* (*RHESSI*) spacecraft (Lin et al. 2002), which observes in a broad range from hard X-ray to γ-ray. Its high spectral res-

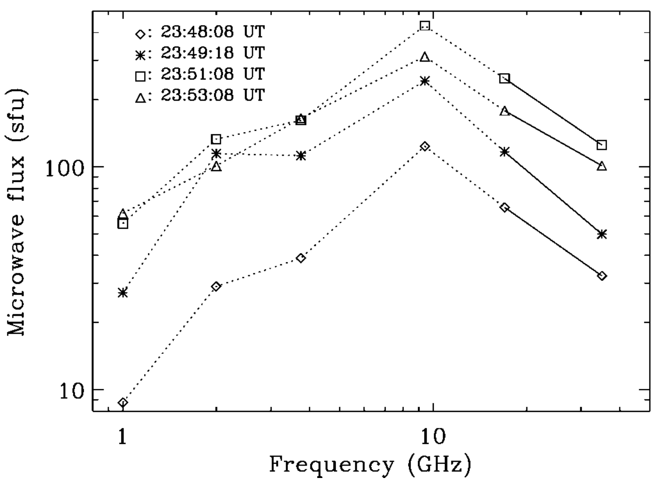

FIG. 1.—Microwave spectral plots at four discrete time intervals for the 2004 May 21 flare. The frequencies of 17 and 35 GHz (*solid lines*) are used to do spectral fitting (see text for details).

olution (1 keV in the X-ray range) and coverage of the low-energy range (down to 3 keV) allow us to separate the thermal continuum from the nonthermal component of the spectrum, and to study power-law spectral evolution from the onset of the flare. We use a forward-fitting method implemented with the OSPEX code to derive the index of the hard X-ray spectrum. The procedure requires us to use a photon spectra model featuring a power law with a low-energy turnover in addition to thermal emission. However, we first have to generate *RHESSI* count spectrograms for each flare in an uninterrupted sunlight time interval with a time binning of 20 s, and an energy binning of 2 keV from 3 to 300 keV. We only use the front segments of the detectors, and excluded detectors 2 and 7.

Figure 2 gives the time evolution of microwave and hard X-ray emissions and their spectral indices for the 2004 May 21 flare. The *GOES* soft X-ray observation shows that this is an M2.7 flare. *RHESSI* observations show magnetospheric par-

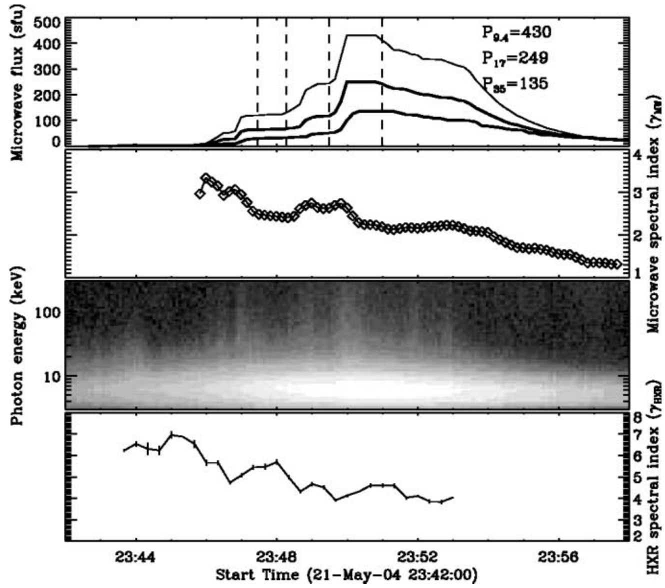

FIG. 2.—Time evolution of microwave (time resolution 10 s) and hard X-ray emission (time resolution 20 s) and their detected spectral indices for the 2004 May 21 flare. Error bars for the hard X-ray spectral index are also shown. Microwave spectra at the four time intervals shown with dashed lines are given in Fig. 1.

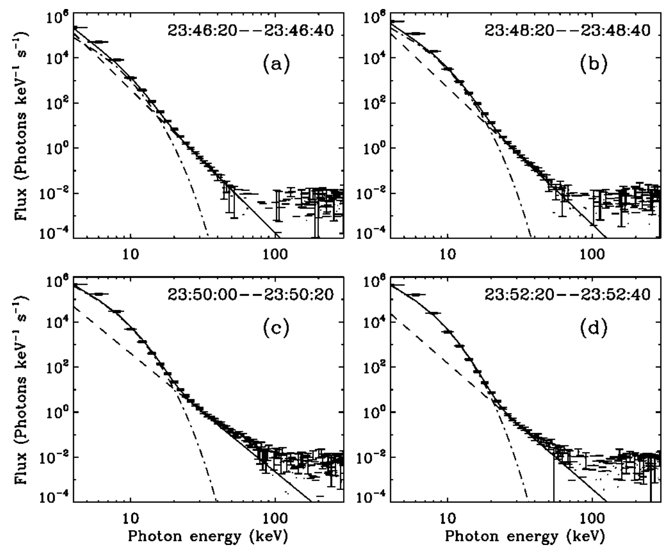

FIG. 3.—*RHESSI* spectra at four discrete time intervals for the 2004 May 21 flare. The points with error bars represent the observational spectral data. Different lines show model spectral fits for thermal bremsstrahlung (*dot-dashed lines*), nonthermal thick-target bremsstrahlung (*dashed lines*), and a summation of the two (*thick solid lines*).

ticles counts during the 2004 May 21 flare; however, the *RHESSI* nonsolar background component changes over the duration of this flare, making the fitting difficult. To properly substract this background is difficult and cannot be done perfectly. Therefore, we restrict the time and energy range for which the fitting is done to times when solar counts dominate. We limit the energy range to between 3 and 40 keV for spectral fitting, and fits after 23:53 UT are problematic. Figure 3 shows the *RHESSI* spectral fitting results at four times.

Using the same method, we do microwave and hard X-ray spectral fitting for the 2004 November 3 flare, which is a M1.6 flare in *GOES* soft X-ray observations. Figure 4 gives the time evolution of the microwave and hard X-ray spectral indices. Figure 5 shows the microwave spectral fitting at four times. For this flare, the hard X-ray spectra are not well represented

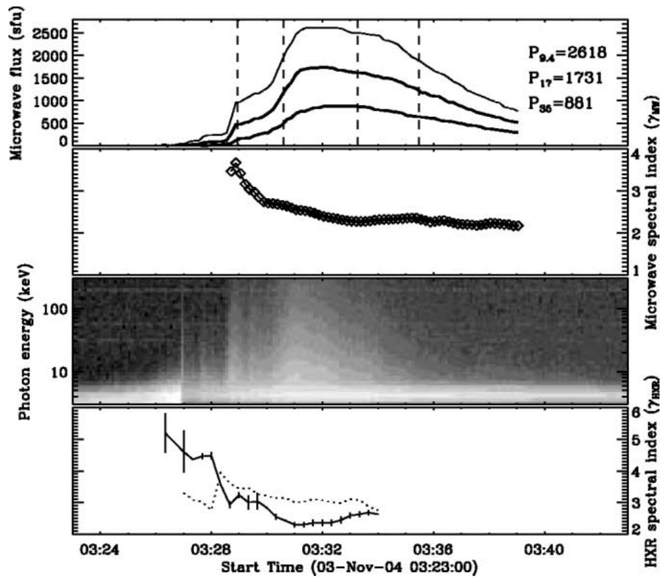

FIG. 4.—As in Fig. 2, but for the 2004 November 3 flare. The solid and dotted lines in bottom panel represent the time evolution of hard X-ray spectral indices at lower and higher energy bands, respectively.

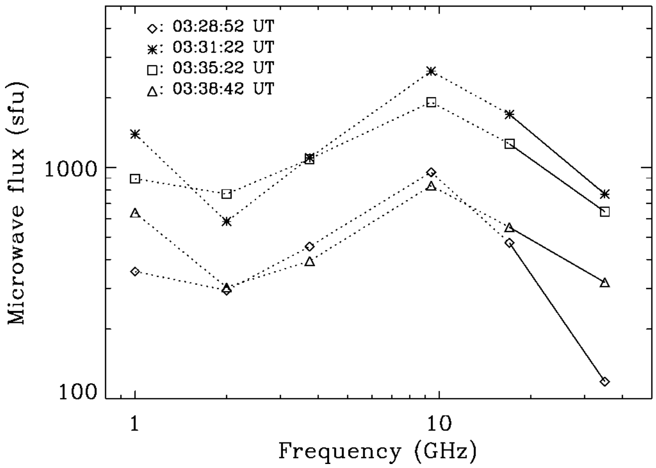

FIG. 5.—As in Fig. 1, but for the 2004 November 3 flare.

by a single power law, but rather show a broken power-law shape. This can be seen in Figure 6 (best seen in the top right and bottom left panels). Thus, we obtain two indices of hard X-ray spectra, shown in Figure 4. In order to rule out the nonsolar background, we restrict the energy range here to between 3 and 100 keV; and fits after 03:34 UT are problematic.

Although each subpeak of the hard X-ray spectrum seems to show a soft-hard-soft behavior, the 2004 May 21 flare displays a spectral hardening in both microwave and hard X-ray emissions from start to end. For the 2004 November 3 flare, the microwave spectra follow a soft-hard-harder behavior. However, the hard X-ray flare shows a soft-hard-soft pattern below the energy break, and a spectral hardening above it.

3. CONCLUSIONS AND DISCUSSIONS

The present observations show that the time series in microwave and hard X-ray flux are correlated. Figure 7 plots the microwave flux at 35 GHz versus the hard X-ray emission at 25–50 keV for two flares. A positive dependence is found in the rise and decay phases, which is consistent with previous results (e.g., White et al. 2003). This fact suggests a common mechanism for the nonthermal electrons. Figure 8 plots this dependence between the microwave and hard X-ray spectral indices. Considering the different time resolution between γ_{MW} and γ_{HXR}, 19 and 25 pairs of points are selected from the time intervals between 23:46:00 and 23:53:00 UT for the 2004 May 21 flare, and between 03:28:40 and 03:34:00 UT for the 2004 November 3 flare, marked by stars and triangles, respectively. Two proportional linear dependences are evident for these points: $\gamma_{MW} = 1.12(\pm 0.12) + 0.37(\pm 0.05) \times \gamma_{HXR}$ and $\gamma_{MW} = 0.54(\pm 0.2) + 0.74(\pm 0.08) \times \gamma_{HXR}$, with 95% confidence level. Although the hard X-ray and microwave emission are produced by electrons at very different energies, a positive correlation between their indices can been seen, indicating a common mechanism for the nonthermal electrons.

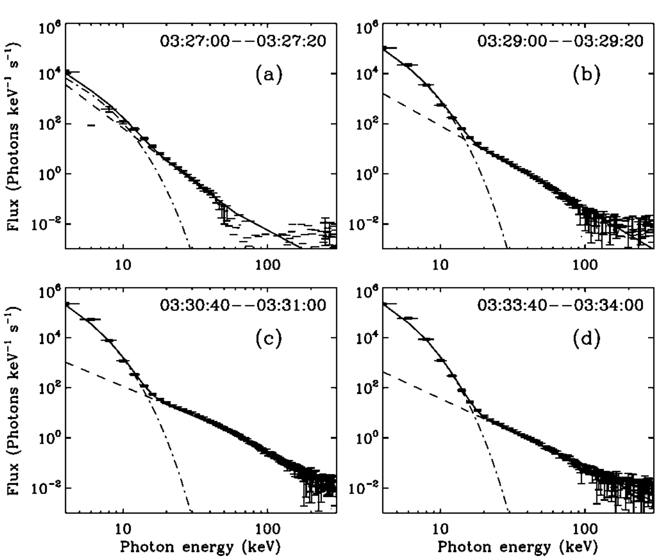

FIG. 6.—As in Fig. 3, but for the 2004 November 3 flare.

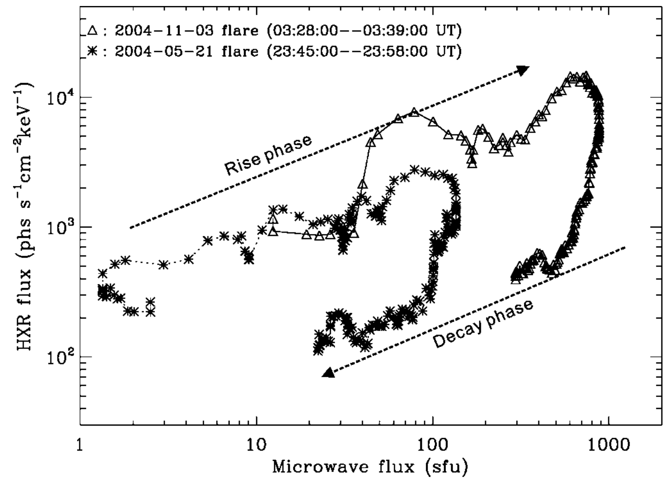

FIG. 7.—Microwave flux at 35 GHz vs. hard X-ray flux at 25–50 keV for the 2004 May 21 flare (*stars*) and 2004 November 3 (*triangles*).

Observations of these two events are consistent with the general flare picture of nonthermal electrons at energies of many hundreds of keV radiating at microwave and at many tens of keV producing hard X-ray emission (e.g., Melnikov & Magun 1998; White et al. 2003). Although both flares show a spectral hardening with time, the microwave spectra are harder than hard X-rays, i.e., $\gamma_{HXR} > \gamma_{MW}$. This implies a broken distribution of nonthermal electrons from tens of keV to several MeV.

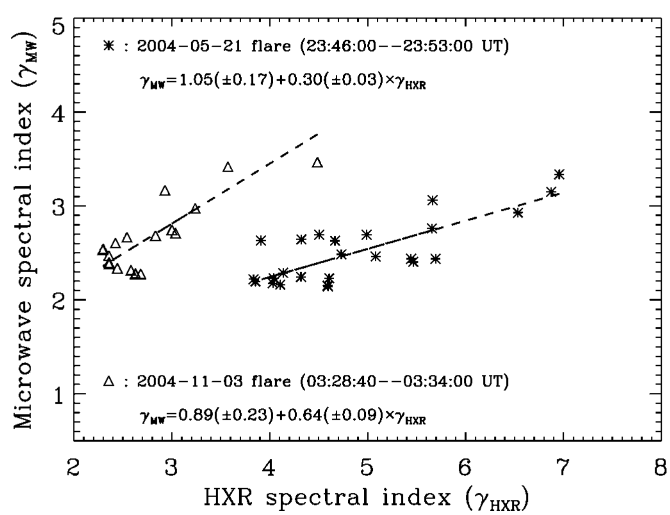

FIG. 8.—Scatter plots of microwave spectral index, γ_{MW}, vs. hard X-ray, γ_{HXR}, for the 2004 May 21 (*stars*) and November 3 (*triangles*) flares. Here 19 and 25 pairs of points are selected from the May 21 and November 3 flares, respectively.

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