Comparison of Microwave and Hard X-Ray Spectra from Solar Flares

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Abstract

We analyze simultaneous hard X-ray and microwave emission from 28 solar flares with multiple peaks. A total of 44 simultaneous peaks were observed at both wavelengths by BATSE (hard X-ray) and Owens Valley Radio Observatory (microwave). Spectra during each burst were fitted throughout the duration of the flare. The hard X-ray spectra were fitted by a single power-law in most cases, whereas the microwave spectra were fitted as gyrosynchrotron emission. The parameters at both wavelengths (peak flux, turnover frequency, duration, spectral indices, and delays between hard X-ray and microwave peak emission) are then compared and correlated for each individual peak. We find that for 74% of the bursts, the inferred index of the electron energy distribution of the microwave emitting electrons, δ_r, is harder than that of the lower energy hard X-ray emitting electrons, δ_x. This implies that there is a breakup in the energy spectra of the electrons, as is sometimes observed in the hard X-ray spectra of giant flares. Moreover, 65% of all bursts with $\delta_x > \delta_r$ also showed delayed radio peak emission with respect to hard X-ray maximum. Implications on electron acceleration mechanisms are discussed.

1. Introduction

It is believed that the hard X-ray and microwave emissions originate from a common population of electrons based on the similarity of their time profiles (Kundu 1961, Kai 1987). This implies that in the majority of flares the hard X-rays produced by the lower energy (< 200 keV) electrons would be the counterpart of the same electron population that give rise to the non-thermal microwave emission from > 300 keV electrons (White and Kundu 1992, Kundu *et al* 1994). However, some giant flares observed by the Solar Maximum Mission satellite (HXRBS and GRS) for which hard X-rays larger than 1 MeV were detected showed a break in their photon spectra around ~300 keV (Vestrand 1988, Dennis 1988). Thus, the spectrum did not follow a single power-law but rather a double power-law with a flatter slope for energies higher than 200-400 keV. Previous comparisons of hard X-ray and microwave/millimeter emission (Kundu *et al.* 1994, Silva *et al.* 1997, Raulin *et al.* 1998) showed that the radio emission was created by a harder electron population than that of the corresponding hard X-rays.

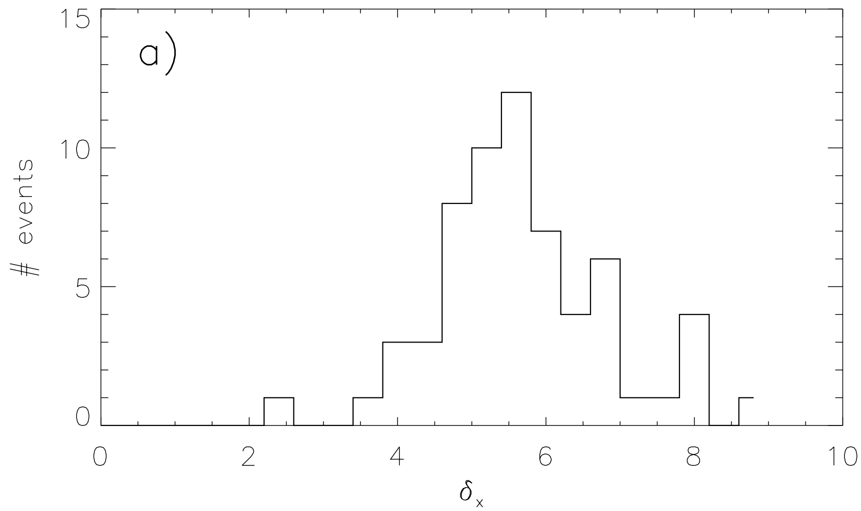
Here we compare microwave and hard X-ray emission from several bursts in order to study the accelerated particles which produced them. The observations are presented in Section 2., with the hard X-rays and microwave data presented separately. Section 3. compares the flare emission and spectral parameters of the two different wavelengths. The constructed electron energy spectra obtained from the observations is discussed in Section 4.. Finally, Section 5. summarizes the main results and describes the conclusions.

2. Observations

A total of 28 flares with 44 peaks were simultaneously observed in hard X-rays with the BATSE instrument on the Compton Gamma-Ray Observatory (CGRO) and in microwaves from 1-18 GHz by the Owens Valley Radio Observatory (OVRO). Many of these flares had multiple peaks which may represent different injections of accelerated electrons onto the flare loop. The hard X-ray and microwave observations are explained in more detail below.

2.1. Hard X-rays

We have used the 16 channel data (16 to 8000 keV) from the Large Area Detectors on BATSE (Schwartz *et al.* 1993). Most of the flares showed emission only up to 200 keV, and only energies greater than 30 keV were used in order to avoid the thermal emission contribution from possible hot sources. The background subtracted data



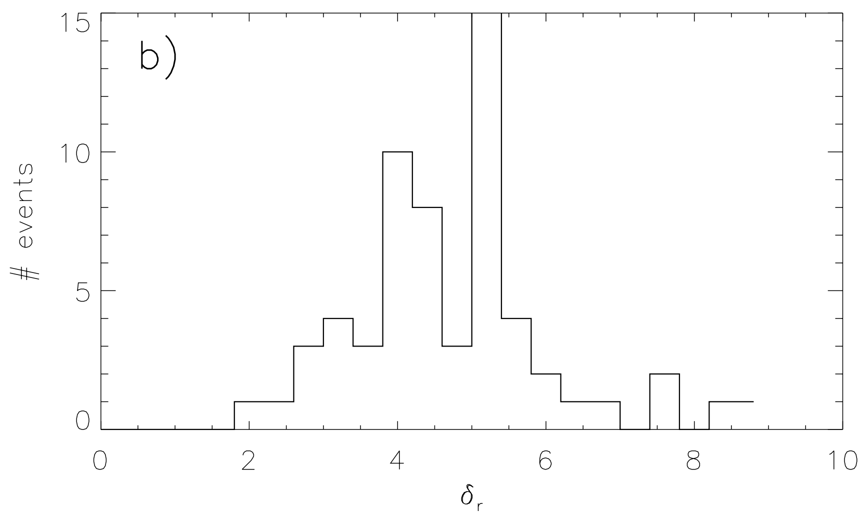


Fig. 1.. Distribution of the electron spectra indices inferred from (a) hard X-ray (δ_x) and (b) microwave (δ_r) spectra.

were binned into 10 second intervals in order to increase signal-to-noise before the spectrum was constructed. Then, the hard X-ray spectrum was fitted by a power-law. Most flares were fit with a single power-law, whereas only 12 bursts were fit by a double power-law. We have computed the photon spectral slope and peak duration for all flares. Assuming thick target for the production of the hard X-rays, the electron energy spectral index, δ_x, can be calculated from the photon spectral slope, γ, by $\delta_x = \gamma + 1.5$.

A histogram of the computed spectral indices, δ_x, is shown in Figure 1.a. The mean value of δ_x is 6.0 with a most probable value of 5.6. This spectral index can then be compared with that obtained for the radio producing electrons.

2.2. Microwaves

The same flares were observed in microwaves at 45 frequencies from 1 to 18 GHz by OVRO with 12 seconds resolution. Here we use only the total power data from the two large antennas. The total intensity data were calibrated and background subtracted. After calibration, the flare spectrum at each time was fitted by a generic

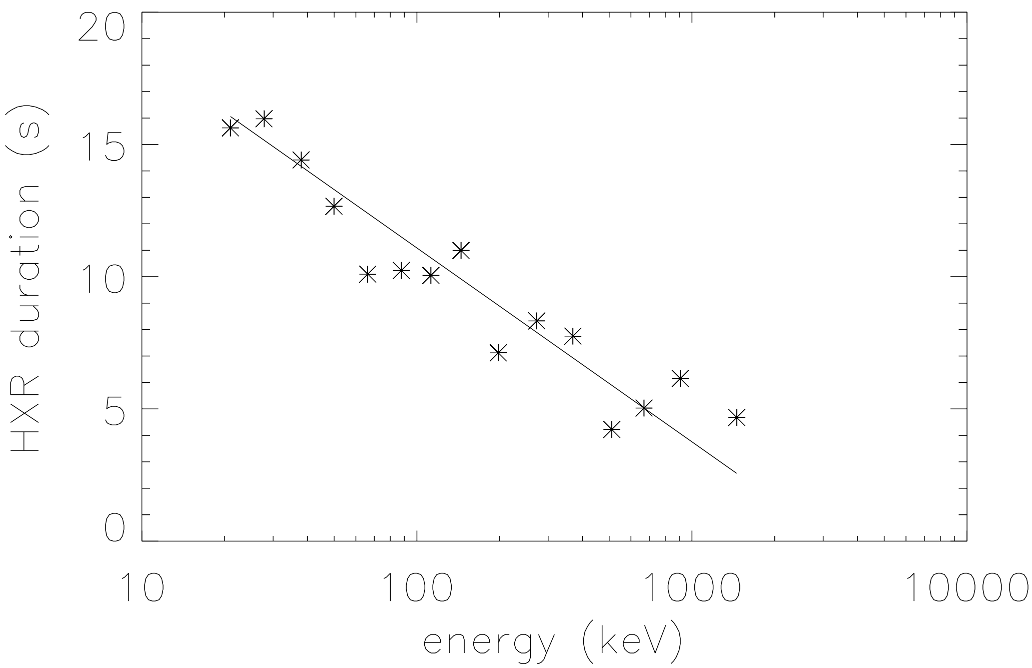


Fig. 2.. Duration of hard X-ray burst as function of the energy of the channel. The solid line is a linear fit to the data; the correlation coefficient of the data is 0.74.

function which has the same shape as gyrosynchrotron emission: $f(\nu) = a_1\ \nu^{a_2}\ \exp(-a_3\ \nu^{-a_4})$

This function yields the low (a_2) and high ($\alpha = a_4 - a_2$) frequency slope as well as the turn over frequency. The turnover frequency, as the name suggests, is where the optically thick spectrum becomes optically thin. This turnover frequency depends on the magnetic field strength at source site and on the density of the emitting electrons. The data show that the spectral peak frequency is normally high. In 35% of the cases the emission only became optically thin at or above 10 GHz. For gyrosynchrotron emission, the optically thin slope, α, is related to the spectral index of the accelerated electrons, δ_r, that emitted the microwaves by $\alpha = 0.9\ \delta_r - 1.22$ (Dulk 1985). The distribution of δ_r values obtained from the fits to the data is shown in Figure 1.b, with an average value of 5. This spectral index, δ_r, can be directly compared with the electron energy index, δ_x, obtained from the hard X-ray data (see Section 4.). Already at first glance, we see that in most cases the δ_r values (Figure 1.b) are lower than those of δ_x (Figure 1.a).

3. Correlation of hard X-ray and microwave data

We have analyzed 44 simultaneous peaks in microwaves and hard X-rays within 25 seconds of each other in order to determine the duration and delays among the microwave and hard X-ray peaks. By fitting the individual time profiles of the peaks as a Gaussian, we have estimated the duration of the hard X-ray peaks. The distribution of duration follows a normal distribution with a mean of 6-8 s. The hard X-ray peak duration was measured for the different energy channels, and Figure 2. shows the mean duration of the peaks at a certain energy as a function of the energy channel. The peak duration is seen to decrease with the energy of the emission. The mean duration of the 24 keV bursts is about 15 s, decreasing to 4 s for the higher energy channels ($\sim$ 1000 keV). This is consistent with a soft-hard-soft behavior seen in the hard X-ray spectra.

Delays between the radio spectral peak flux and the 30 keV emission were determined by calculating the cross-correlation of the time profiles of the individual peaks for the different wavelengths. In order to do the cross-correlation, we have interpolated the radio data to the hard X-ray time intervals of 2 seconds. For 27% of the bursts no delays were measured (0 - 2 s). On the other hand, 61% of the peaks showed $>$ 2 s delays. These measurements

Table 1. Spectral Index Behavior.

peak order	HXR		Radio	
	SHS (%)	SHH (%)	SHS (%)	SHH (%)
1	34	10	29	15
2	29	9	19	19
3	3	10	3	10
4	2	3	2	3
total	68	32	53	47

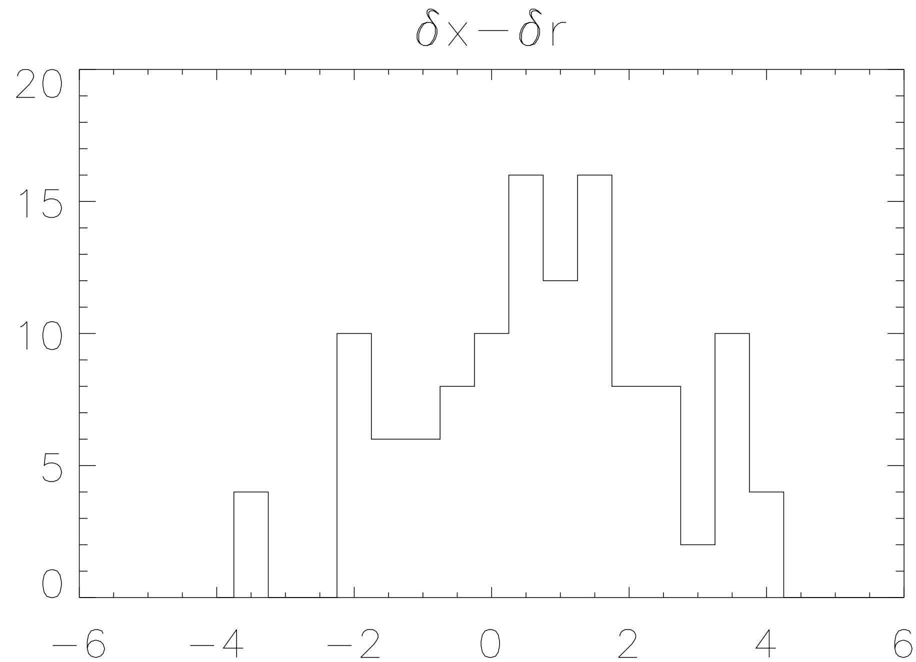


Fig. 3.. Histogram of the difference between δ_x and δ_r.

suggest that for the majority of the bursts, the higher energy electrons reached their maximum emission a few seconds after the lower energy electrons.

We have studied the spectral indices temporal behavior separately for hard X-ray and microwave emission for a total of 44 bursts. Two possible behaviors are considered: soft-hard-soft (SHS) where the spectral index hardens at peak time, becoming soft again right after it, or soft-hard-harder (SHH), where the index continues to harden after the temporal maxima. Table 1 lists the percentage of cases observed for the hard X-ray and radio data as functions of peak order. The hard X-ray peaks showed SHS behavior for 68% of the cases against 32% of SHH. For the microwave peaks, 53% of them presented SHS behavior against 47% of SHH. That is, a continuous hardening of the spectrum is seen more frequently in the higher energy electrons. Moreover, we see from the data listed in Table 2 that the SHS behavior is more commonly seen during the first peak, whereas SHH is, on average, equally probable of occurring in the first and later peaks. This is observed in both hard X-ray and microwave spectra. A persistent hardening may be the result of continuous injection of accelerated electrons into the flare loop.

4. Electron energy spectra

As we have mentioned previously, the hard X-rays observed in the flares reported here were created by < 200 keV electrons, whereas the microwaves were generated by gyrosynchrotron processes from > 300 keV electrons. Thus, by combining the spectral information at both wavelengths we may estimate the shape of the electron energy spectra from low to high energies.

Figure 1. already hinted that the inferred electron spectral index from hard X-rays is steeper than that estimated from microwave data. If emission at both wavelengths were produced by the same electron population, then one expects $\delta_x \sim \delta_r$, when dynamic effects can be neglected. In Figure 3. we plot the difference between the spectral indices, $\delta_x - \delta_r$. As can be seen from the figure, the maximum of the distribution is not around zero but rather in the range 0.5-2.0. In 74% of the cases, the electron spectral index determined from the radio spectra, δ_r, is harder than that obtained from the hard X-rays, δ_x. Moreover, 65% of the observed peaks with $\delta_x > \delta_r$ also showed delayed microwave emission with respect to the hard X-ray peak.

5. Discussion and Conclusions

From a study of 44 peaks observed in 28 flares, for which delays and duration were determined, we obtain the following results:
1) Most of the bursts showed a delay between the hard X-ray peak and the microwave maxima;
2) Soft-hard-soft behavior of spectra is more commonly seen during the first peak rather than later ones. The SHH behavior is more common in the microwave spectra (47% of cases) than in hard X-ray spectra (32% of cases);
3) δ_r is harder than δ_x by 0.5-2.0 for the majority of bursts (74%);

The main result from this study is that for most of the flares:

$$\delta_x > \delta_r \tag{1}$$

implying a breakup in the energy spectrum of the accelerated electrons. That is, the energy distribution of the higher energy electrons (which produce the radio emission) is harder than that of the lower energy electrons (which give rise to the hard X-rays). Break ups in the electron spectra have been reported previously in the literature with millimeter observations (Kundu *et al.* 1994, Chertok *et al.* 1995, Silva *et al.* 1997, Raulin *et al.* 1998) and in hard X-ray spectra for a few cases of giant flares (Vestrand 1988, Dennis 1988).

On the other hand, using SMM/HXRBS observations, Dulk, Kiplinger and Winglee (1992) found that most of the 174 peaks studied displayed a break down in their spectra, the break energy being around 100 keV. From the 44 BATSE bursts studied here only 12 showed a broken power-law, with 9 displaying a broken-down spectra, as observed by Dulk *et al.* (1992), against 3 broken-up spectra. Nevertheless, out of these 9 events with broken-down hard X-ray spectra, 7 had a flatter spectral index from the microwave data, implying a spectrum which break down at < 100 keV and a further break-up at > 200 keV energies. These 7 events had hard X-ray data up to 200 keV.

A breakup in the electron energy spectrum may be explained: (1) by two different electron populations being accelerated in different sites with distinct physical conditions, (2) by a "trap plus precipitation" model, or (3) by a second-step acceleration mechanism (Wild *et al.* 1963, de Jager 1969, Bai and Ramaty 1976, Svetska 1976, Ramaty *et al.* 1980). In the latter case, a first acceleration phase produce the electrons which emit the hard X-rays. A suggested mechanism has been DC electric fields along the magnetic field (Dulk *et al.* 1992, Lin and Schwartz 1987), which would accelerate electrons up to 100-200 keV. These electrons are then further accelerated by another mechanism producing the higher energy electrons that gave rise to the radio emission by gyrosynchrotron. This acceleration could be some kind of wave-particle interaction (Winglee *et al.* 1991) or shocks. In any case, a delay between the higher energy electrons emission and that of the lower energy electrons is expected. We did observe the microwave emission (higher energy electrons) to peak after the hard X-rays, produced by the lower energy electrons, in most flares.

The "trap plus precipitation" model takes into account the dynamics of the injected energetic particles which are trapped into a closed magnetic loop (Melrose and Brown 1976, Vilmer *et al.* 1982, MacKinnon *et al.* 1983, Hulot *et al.* 1992). The model predicts a hardening of the spectra of the trapped electrons due to the losses of lower energy electrons by energy-dependent Coulomb collisions (Trottet and Vilmer 1984). In this case, the radio emission produced by the electrons in the trap would reflect this hardening while the hard X-ray spectra generated by the precipitated electrons would still preserve the original injection spectrum, which is softer. This model also predicts a delay between hard X-ray and radio emission maxima. Melnikov and Magun (1998) explain the observed spectral flattening in time of microwave/millimeter spectra of 20 flares they observed in the light of the "trap plus precipitation" model.

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