GAMMA-RAY LINE VERSUS CONTINUUM EMISSION OF ELECTRON-DOMINATED EPISODES DURING SOLAR FLARES

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Abstract. Electron-dominated episodes or events during solar flares are characterized by a flattening of the electron bremsstrahlung continuum above about 1 MeV. This flattening leads to a dominance of the continuum at MeV energies over nuclear emissions. We analyzed events recorded by the gamma-ray spectrometer on SMM with the aim to determine the nuclear contribution in the energy range between 4 and 8 MeV. We find that for comparable continuum fluences it is less by about an order of magnitude than for other flares. The spectral index of the best-fit power law of the > 1 MeV continuum with a median at -1.84 turns out to be independent of the heliocentric angle of the events, implying that the degree of anisotropy of the radiating particles was low. It is of interest to note that a value of ~ -1.5 seems to be a limit. The spectral index of the continuum between 0.3 and 1 MeV does not differ significantly from that of other flares. Only measurements with detectors sensitive up to at least 10 MeV can, therefore, sort out electron dominated episodes during solar flares.

1. Introduction

The emission during solar flares in the energy range from 0.3 to 10 MeV is a superposition of continuum and nuclear line radiation. It was estimated and shown by measurements that at energies from 0.3 to 1 MeV a continuum originating from electron bremsstrahlung and above $\sim$ 1 MeV nuclear line radiation dominates the flare spectrum (Ibragimov and Kocharov, 1977; Ramaty, Kozlovsky, and Suri, 1977; Forrest, 1983; Chupp, 1984). This important fact facilitates the separation of the ionic from the electronic component. It is customary to approximate the continuum by a best-fit power law and to extrapolate it to higher energies. The excess above this extrapolation, which is intense especially between 4 and 7 MeV, is then ascribed to nuclear interactions. From the separated fluences, the number and spectra of the respective constituents can be calculated (Ramaty and Murphy, 1984; Ramaty *et al.*, 1993).

There are, however, energetic episodes during solar flares recorded by the Gamma-Ray Spectrometer (GRS) on SMM whose spectra differ substantially from the conventional picture. The spectra are basically continua in the whole energy range from 0.3 to 10 MeV and beyond, with a tendency to flatten around 1 MeV, and the contribution of nuclear lines above 1 MeV is small (Rieger and Marschhäuser, 1990). They also do not exhibit a marked drop above 7.2 MeV, which

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is obvious in nuclear line events, resulting from the absence of intense nuclear lines above this energy (Rieger, 1991; Share and Murphy, 1995). It is generally accepted that this high-energy continuum also originates from electrons (Hudson and Ryan, 1995). This type of flare or burst is, therefore, called 'electron dominated' or 'electron rich', to distinguish it from other (normal) flares (Rieger and Marschhäuser, 1990; Hudson and Ryan, 1995). These events have been observed from other detectors in space, too, for instance by PHEBUS on GRANAT (Pelaez *et al.*, 1992; Vilmer, 1994; Vilmer and Trottet, 1997), by GAMMA-1 (Akimov *et al.*, 1994), by BATSE, COMPTEL and EGRET on CGRO (Ramaty *et al.*, 1994; Ryan *et al.*, 1993; Dingus *et al.*, 1994, respectively), by the WBS on *Yohkoh* (Yoshimori *et al.*, 1993) and possibly also by *Hinotori* (Yoshimori, Okudaira, and Yanagimachi, 1986).

In this paper we investigate the contribution of the nucleonic emissions to the fluence above 1 MeV of GRS electron-dominated events and compare it with other flares, and inspect the dependence of the spectral index of the high-energy continuum on the heliocentric angle. Finally, we check whether the spectral slope below 1 MeV discriminates between electron-dominated events and other solar flares.

2. Observations

In Table I the GRS electron-dominated episodes or events during flares are listed, which were intense enough to be spectrally analyzed in the nuclear energy range above 1 MeV. All these events show a prominent signal above 10 MeV. This was the prime condition for their selection from the main flare list. The second condition was that the continuum, not lines, is the dominant contribution within the nuclear energy range. A clear hint for this is the fluence contained in the energy interval from 7.2 to 9 MeV (GRS upper photon energy limit), which is much higher than the 0.3−1 MeV power-law extrapolation for these events. However, a $>$ 10 MeV emission can also originate from pion decay (see Murphy, Dermer, and Ramaty, 1987). It is of importance to note that only for two flares in which the electron-dominated events occurred was pion decay radiation recorded: (1) event No. 4 is a precursor of the energetic 3 June 1982 flare (Forrest *et al.*, 1985; Rieger, 1994); (2) during event No. 9 pion decay radiation was observed (Dunphy and Chupp, 1991), but the contribution to the emission below 10 MeV is negligible. As already mentioned, the most probable source of the $>$ 1 MeV continuum of all the listed events is, therefore, electron bremsstrahlung.

The temporal histories of the events, except No. 1, are already published as indicated in column 6 of Table I by superscripts. $\triangle t$ in column 6 is the time interval over which the flare or event is spectrally analyzed and f in column 7 is the fractional time interval of the gamma-ray flare over which it was electron dominated. As the temporal resolution of the GRS is 16.384 s, $\triangle t$, in most cases, is a multiple of this value. For events No. 8, 10 and 12, however, a short burst

TABLE I
GRS electron-dominated events

Event No.	Day M/D/Y	Flare	Θ (deg)	Time (UT)	Δt (s)	f (%)
1	06.04.1980	M6.7/SB	60	06:54:19	49	100
2	10.14.1981	X3/SB	87	17:05:44	82[1]	100
3	02.08.1982	X1.4/1B	87	12:49:17	82[2]	56
4	06.03.1982	X8/2B	72	11:42:44	16[1]	1.2
5	06.15.1982	M5.4/1B	90	00:30:31	16[3]	20
6	05.07.1983	X3.1/2B	68	22:17:57	49[1]	37
7	03.06.1989	X13/3B	77	13:57:13	98[3]	2.9
8	03.06.1989	X13/3B	77	13:59:23	4[3]	0.12
9	03.06.1989	X13/3B	77	14:01:34	131[3]	3.8
10	03.10.1989	X4.5/3B	44	19:20:00	8[3]	0.29
11	03.16.1989	X3.6/2B	62	15:24:30	32[4]	8.5
12	06.14.1989	M2.7/1F	76	13:52:40	8[3]	25

[1]Rieger, 1994;
[2]Kane *et al.*, 1986;
[3]Rieger and Marschhäuser, 1990;
[4]Rieger *et al.*, 1996.
Flare importance and position from NOAA-USAF SESC *Preliminary Report and Forecast of Solar Geophysical Data.*

dominated the emission during the 16 s time window, as evidenced from the high time resolution (2.048 s) of the ‘main channel window’ between 4.1 MeV and 6.4 MeV, and from the high-energy channels above 10 MeV (Forrest *et al.*, 1980). For these events we assume that the spectral slope does not change within the 16 s time window, and the spectral constant is calculated according to the fluence of the burst, with respect to the whole 16 s time interval.

The spectra were deconvolved by applying the Singular Value Decomposition (SVD) method (Marschhäuser, 1993). As already mentioned, the spectra of the electron dominated events flatten above about 1 MeV. The continuum is approximated by a broken power law of the form $A_{1,2}E^{\gamma_{1,2}}$, where $A_{1,2}$ is essentially the differential intensity at 1 MeV and the subscripts refer to the power law below and above 1 MeV, respectively. As usual, the excess between 4 and 8 MeV above the power law – here the power law above 1 MeV – is ascribed to nucleonic interactions. For ‘normal’ flares the power law above 1 MeV is an extrapolation from lower energies. For electron-dominated events the power law above 1 MeV is an observable quantity. In Table II the spectral parameters of the events of Table I are listed.

TABLE II

Spectral parameters

Event No.	A_1 > 0.3 MeV γ MeV^{-1} cm^2	Index 1 > 0.3 MeV	A_2 > 1 MeV γ MeV^{-1} cm^{-2}	Index 2 > 1 MeV	Φ 4–8 MeV γ cm^{-2}
1	14.5[(1)]	-2.40 ± 0.1[(1)]	14.5	-1.88 ± 0.1	1.7 ± 0.4
2	300	-2.63 ± 0.03	300	-2.26 ± 0.1	10.7 ± 4
3	120	-2.81 ± 0.03	120	-2.10 ± 0.1	3.5 ± 2
4	67	-2.83 ± 0.05	67	-2.08 ± 0.1	$2.16^{+2}_{-1.4}$
5	7 ± 1.2	-2.85 ± 0.18	8.5 ± 1	-1.51 ± 0.05	$0.93\ ^{+0.7}_{-1.0}$
6	541	-2.49 ± 0.05	541	-2.21 ± 0.12	16.5 ± 10
7	770	-2.40 ± 0.05	770	-1.45 ± 0.1	22 ± 3[(2)]
8	57	-2.47 ± 0.05	57	-1.69 ± 0.05	1.2 ± 1
9	772	-2.82 ± 0.1	772	-1.96 ± 0.1	46 ± 7[(2)]
10	8.6 ± 1.1	-3.01 ± 0.15	8.6 ± 1.1	-1.55 ± 0.15	0.8 ± 0.8
11	72	-3.04 ± 014	72	-1.56 ± 0.05	3.7 ± 4
12	14.5 ± 1	-3.0 ± 0.1	18.5 ± 2	-1.87 ± 0.1	1.7 ± 0.7

[1] Vestrand *et al.* (1987) ;

[2] Marschhäuser, Rieger, and Kanbach (1994).

Event No.	Time interval [UT]	Φ (2.2 MeV) (γ cm^{-2})
1	06:54:19 – 06:55:57	1.5 ± 0.7
7	13:57:46 – 14:01:52	23 ± 1
12	13:52:33 – 13:55:00	2.5 ± 0.5

Column 6 contains the nuclear excess fluence between 4 and 8 MeV deduced for the time interval, listed in Table I (column 6). A valuable proxy for nucleonic interactions is also the fluence of the neutron capture line at 2.223 MeV. Where possible (events No. 1, 7 and 12) this value has also been determined. It is listed below Table II, corrected for off-disc-centre position (Hua and Lingenfelter, 1987). For the other events, the 2.223 MeV line fluence could not be determined because they were too close to the solar limb, they occurred shortly before Earth occultation of SMM, or they were in close temporal proximity to other flare bursts.

In Figure 1 the 4–8 MeV nuclear excess fluence of the electron-dominated events versus the > 0.3 MeV continuum fluence is inserted into a graph compiled by Vestrand (1988), who analyzed the GRS flares up to February 1986. Events No. 1–6 are, therefore, contained in Vestrand's graph, but, contrary to our procedure, where the nuclear excess fluence is determined by subtracting the > 1 MeV continuum, the extrapolated > 0.3 MeV power-law continuum was subtracted. Moreover, only for events No. 1 and 2 was the same time interval used. The large er-

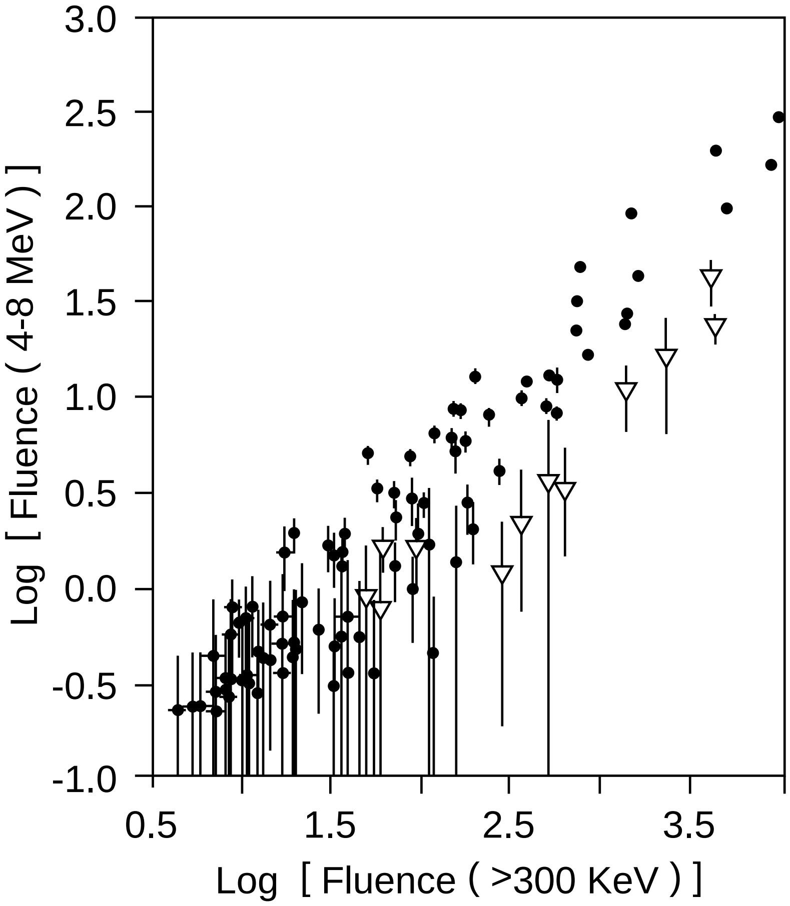

Figure 1. Correlation plot for 4–8 MeV excess versus the continuum fluence above 300 keV. *Full dots*: compilation of Vestrand (1988). *Open triangles*: electron-dominated events.

ror bars are mainly caused by the uncertainty in defining the slope of the $>$ 1 MeV power law. Event No. 9 marks a transition between an electron-dominated episode and a normal flare. It is apparent that for most of the electron-dominated events a nuclear excess can be reliably determined, but it is lower by almost an order of magnitude than for other flares. There is an indication that at low continuum fluences both types of events begin to merge.

In Figure 2 the nuclear excess fluence is plotted versus the $>$ 1 MeV continuum fluence. This kind of representation is more appropriate to our situation, because electron-dominated episodes are characterized by the dominance of the continuum above 1 MeV. We left out those flares from Vestrand's sample which have a convex (as seen from above) shape of the continuum from 0.3 to 1 MeV, because the $>$ 1 MeV extrapolation then becomes erroneous. As one would expect, the gap

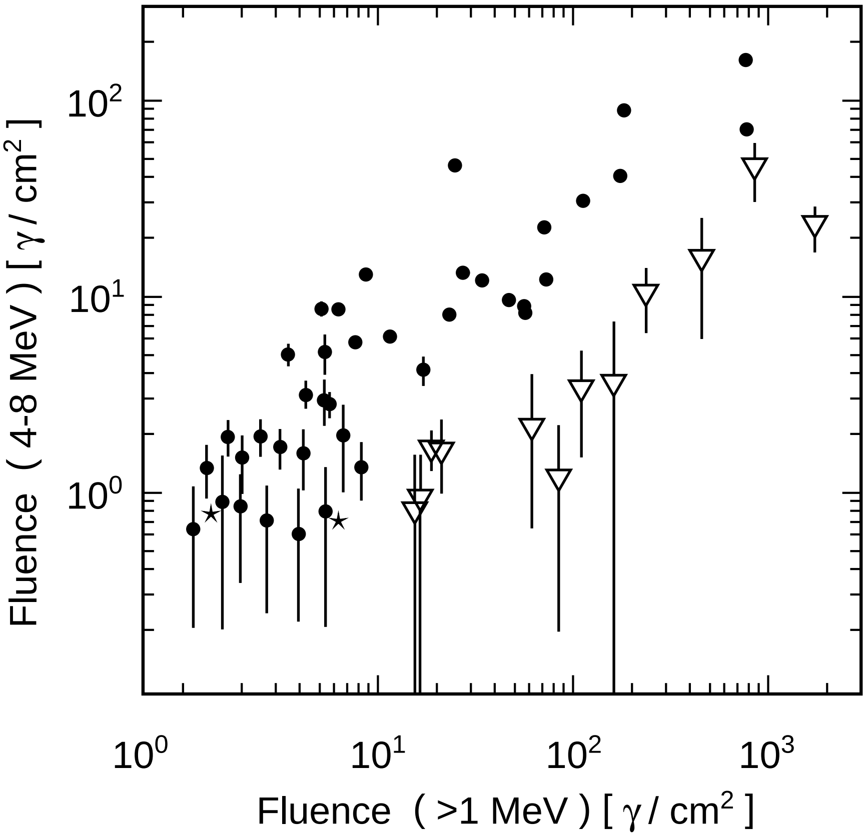

Figure 2. Correlation plot for 4–8 MeV excess versus the continuum fluence above 1 MeV. *Full dots*: $>$ 1 MeV continuum fluence calculated according to Vestrand *et al.* (1987, Table I). *Open triangles*: electron-dominated events. *Asterisks* : 4–8 MeV fluence inferred from 2.2 MeV line fluence by equating both values (Ramaty *et al.*, 1993).

between both types of events increases and the tendency to merge at low continuum fluences is fading.

3. Discussion

Because the continuum above 1 MeV of the non-electron-dominated events or flares is not really observed, we have to ask how Figure 2 changes in case the slope should differ from the extrapolated value. If it steepens above 1 MeV, the full dots would be shifted to the upper left and the separation between both types of events gets larger. If it flattens, the separation gets smaller. The latter case is unlikely, because then we would observe excess emission between 7.2 and 9 MeV and above 10 MeV, and these events or flares would be assigned to the type ‘electron-dominated’.

An important point is the directionality of the high-energy photons. This topic was revitalized by the observation that flares with photon emission above 10 MeV are located preferably near the solar limb (Rieger *et al.*, 1983; Vestrand *et al.*, 1987; Vestrand, Forrest, and Rieger, 1991; Talon *et al.*, 1993), suggesting that the distribution of the radiating particles is anisotropic. Calculations by Dermer and Ramaty (1986) showed that for electrons having a horizontal distribution, the bremsstrahlung continuum is enhanced with respect to an isotropic distribution for flares which are close to the solar limb. This enhancement depends upon the degree of anisotropy and of the energy of the radiating electrons. The heliocentric angle of our events (column 4 of Table I) is between 44° and 90°. We, therefore, should expect that the continuum above 1 MeV of the electron-dominated events is overestimated compared to the sample of Vestrand. This fact would reduce the gap between electron-dominated events and other flares in Figure 2. The directionality of the electrons, however, should also influence the spectral index of the > 1 MeV continuum in the sense that it decreases (in absolute magnitude) with heliocentric angle (see Vestrand *et al.*, 1987). Contrary to this expectation, we see in Figure 3 that it is independent of the position at the Sun. There is also no heliocentric angle dependence when one takes the difference between the low-energy and the high-energy spectral indices. This surprising finding implies that the degree of anisotropy of the radiating electrons is probably low and, therefore, the correction to be applied to the continuum flux of the electron dominated events in Figure 2 is negligible. (For further discussion see Mandzhavidze and Ramaty, 1993.)

The gap, which separates both types of events in Figure 2, is tempting to conclude that electron-dominated episodes or events during solar flares constitute a special phenomenon of the active Sun. A less spectacular assumption, however, is that the gap results from the small number of these events in our flare sample and that further measurements with larger and better detectors would lead to a filling-in (event No. 9). In this case, electron dominated episodes during flares are events with extreme spectral properties (Trottet *et al.*, 1998). We conjecture that the small number of nuclear lines is caused by the preponderance of an acceleration mechanism that does not preferably accelerate protons or ions with respect to electrons. If electrons and protons are accelerated to high energies with about the same efficiency, gamma-ray lines begin to disappear in the strong electron continuum. A mechanism with these characteristics is acceleration by DC electric fields (Haerendel, 1994), which is known and very well observed in the Earth's magnetosphere (Haerendel *et al.*, 1976; Haerendel, 1987). For alternative explanations of the spectral properties of electron-dominated events see Bech, Steinacker, and Schlickeiser (1990), Petrosian, McTiernan, and Marschhäuser (1994) and Park, Petrosian, and Schwartz (1997).

It is also of interest to note that the power law spectral index of the continuum above 1 MeV has an apparent limit around -1.5. If this limit should be confirmed by future measurements, it could be of importance to sort out the prevalent acceleration mechanism.

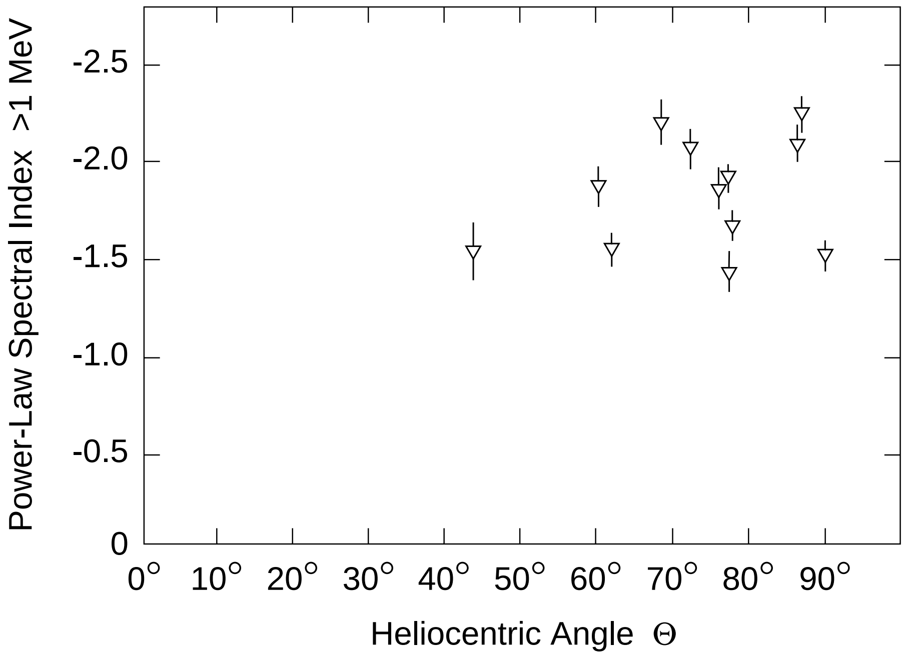

Figure 3. Power-law spectral index above 1 MeV of electron-dominated events versus heliocentric angle.

Finally, we check the possibility of discriminating electron-dominated events from other solar flares by the spectral slope below 1 MeV. This question arises, because flare measurements in the gamma-ray regime, due to the need for big detectors, are much rarer than at high-energy X-rays. As a test sample, we use the GRS flares analyzed by Vestrand *et al.* (1987). The median of the spectral indices between 0.3 and 1 MeV was about 2.9 (Vestrand, 1988). By taking only those flares, which occurred at a heliocentric angle of $\geq 60°$ the median shifts to 2.77. The fact that some of the electron-dominated events are among these flares, is not of importance. The median of the spectral indices of our electron-dominated events is 2.73. This clearly demonstrates that the spectral slope below 1 MeV cannot be used to sort out electron-dominated events from normal flares. Only measurements carried out with gamma-ray spectrometers sensitive up to at least 10 MeV can reveal the special properties of these events. The gamma-ray detector on SMM had these capabilities, which led to their discovery.

4. Conclusion

The interpretation of electron-dominated or electron-rich events is a major challenge (see Miller *et al.*, 1997). A viable theory has not only to explain the flat photon spectrum at MeV energies and the low contribution of gamma-ray lines, but also the high degree of impulsivity of some of these events, which is almost reminiscent of cosmic gamma-ray bursts. Moreover, it is surprising that the spectral slope above 1 MeV is independent of the heliocentric angle, suggesting that the degree of anisotropy of the radiating particles is small. This could mean that they occur on very small loops (Mandzhavidze and Ramaty, 1993).

Important progress in the understanding could be reached by spatially locating these events. As it is not possible to get arcsecond resolution at MeV energies in the near future, we will have to rely on flare observations with high spatial resolution at lower energies and make correlations on the basis of simultaneous appearances.

Further observations, especially with high-spectral-resolution Germanium gamma-ray spectrometers, are needed to investigate if there are extreme electron dominated events, which are virtually void of gamma-ray lines as indicated in events No. 5, 10 and 11. Such an instrument could also extend the measurements to very low continuum fluences in order to clarify if electron-dominated events will merge there with normal solar flares. These topics could be a target of the approved HESSI mission (Holman *et al.*, 1997).

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