Spectral Evolution of an Intense Gamma-Ray Line Flare

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The flare of 16 December 1988 is one of the most intense gamma-ray line events that the Gamma-Ray Spectrometer (GRS) on SMM has recorded. It proceeded in several well separated bursts. By taking the fluences of selected energy bands, the spectrum of the primary particles can be determined. We find that it changes from burst to burst, suggesting even different acceleration mechanisms.

INTRODUCTION

In no other situation than during Solar flares the acceleration of charged particles can be explored in such great detail, because (a) events can be studied in their temporal history and (b) the Sun is near enough to investigate the phenomenon in a very wide energy range from X-rays to gamma-rays, where the accelerated particles leave their fingerprints most clearly. The flare of 16 December 1988 is one of the biggest gamma-ray line events recorded by the GRS on SMM (1). It shows emission also above 10 MeV and was, therefore, investigated for high energy neutron emission and for pion decay radiation (2) (3) (4). These papers deal primarily with a burst that exhibited high flux beyond 10 MeV photon energies. As the flare proceeded in several well separated bursts, the spectral evolution from burst to burst can be studied, which is the purpose of this paper.

OBSERVATIONS AND DISCUSSION

The X4.7/1B flare which occurred in NOAA Active Region 5278 at a heliographic position of N26E37 on 16 December 1988 (Preliminary Report and Forecast of Solar Geophysical Data, SESC PRF 694) was very much extended in time. Its temporal history is shown in Figure 1 at high energy X-rays and at selected gamma-ray energy bands. From measurements at low energy X-rays carried out with our small X-ray spectrometers (not shown in the Figure) we deduce that SMM came out of Earth ecclipse around 0829 UT, when the flare was already on. However, the fact that the flux of the 2.2 MeV neutron capture line (panel 3 of Figure 1) began to increase not before 0832 UT tells us that the flare got energetic after the night-day passage of SMM. Next satellite night begins around 0927:30 UT when the flare presumably faded away,

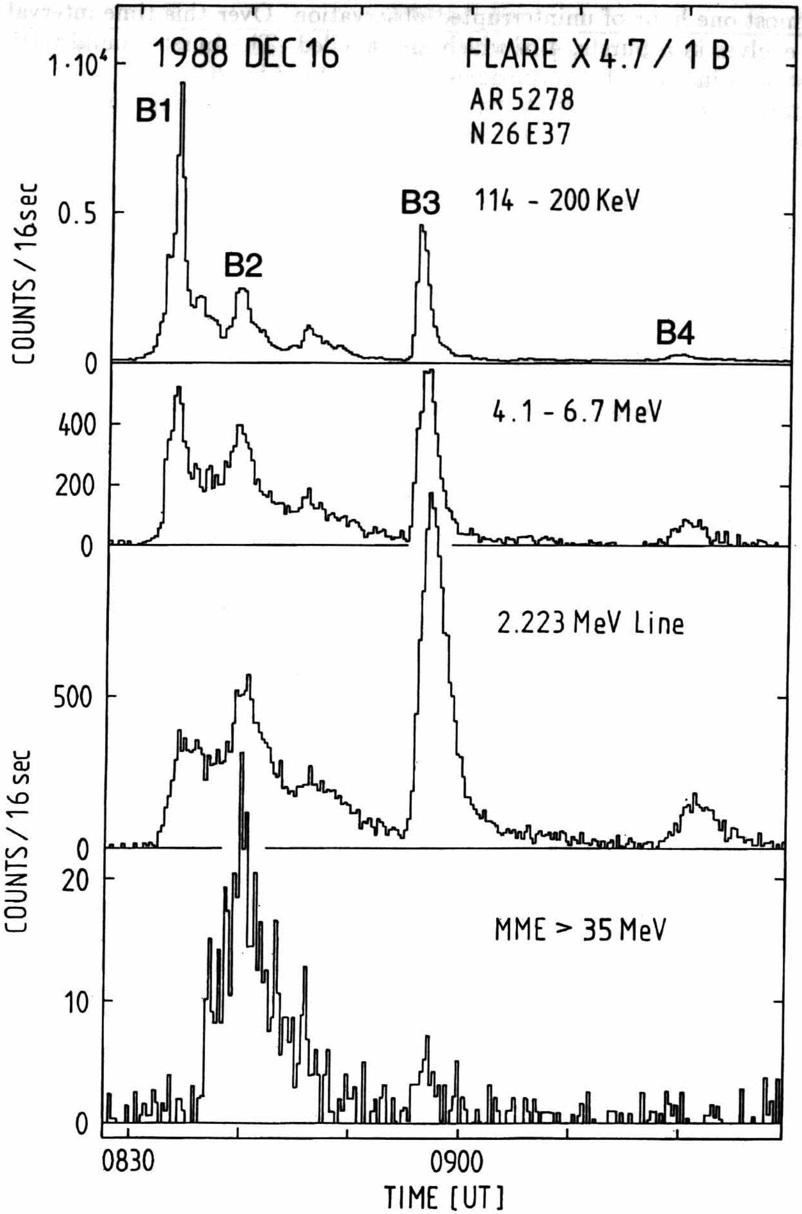

FIG. 1. Temporal history of the 16 December 1988 flare in different energy bands

giving almost one hour of uninterrupted observation. Over this time interval the flare evolves in 5 bursts, 4 of which are labelled. The burst around 0845 UT (best seen in panel 1) is considered a satellite of burst 2.

The energy range 4.1-6.7 MeV (panel 2) contains the strong nuclear de-excitation lines of Carbon and Oxygen. It is shown without reduction of a continuum from bremsstrahlung of high energy electrons. But in this energy range and for this special flare the continuum, which is determined at lower energies (0.3-1 MeV) and extrapolated to the nuclear energy range by assuming a power law (5), is mostly below 20total signal, so that the graph shown is a good representation of the nuclear excess radiation.

In panel 3 the flux of the 2.223 MeV neutron capture line is plotted. With an overall fluence of 610 $\pm$ 30 $\frac{\gamma}{cm^2}$ this event was one of the most prolific line flares that the GRS recorded (see also (1)).

In panel 4, named MME, events with energy losses above 35 MeV are shown which lead to a signal in the upper (NaJ) and lower (CsJ) part of the detector (6) (7) (8). As calculations have shown (9), these events are produced mainly by high energy gamma-ray photons. Signals due to high energy neutrons entering the spectrometer are suppressed by this method effectively. The measurement then is a superposition of a continuum resulting from bremsstrahlung of very high energy electrons and of pion decay photons. As shown by Alexander et al. (4), however, the bremsstrahlung component is negligible above 35 MeV.

The ratio of the neutron capture line fluence and the 4-7 MeV nuclear excess radiation fluence is a measure of the hardness of the primary proton spectrum at medium energies from about 10 to 100 MeV (10). We, therefore, see from an inspection of panel 2 and 3 of Figure 1 that the spectrum of the energetic particles must have hardened progressively from burst 1 to 3. Because of the delayed character of the 2.2 MeV neutron capture line, however, it is not sufficient to calculate the ratio of the fluences by taking the respective fluxes of certain time intervals. Following Prince et al. (11) we use the 4-7 MeV nuclear excess flux as the temporal injection profile of the energetic particles which is a measure of the production rate of the neutrons. The capture of these neutrons on Hydrogen and 3He and their decay determines the decay time of the 2.2 MeV line flux. The neutron production rate and the 2.2 MeV line decay time are varied until a sufficient agreement between the calculated and measured 2.2 MeV line flux versus time is obtained. The time intervals for the bursts are chosen as follows : (1) 0830:12 - 0835:56 UT; (2) 0835:56 - 0854:46 UT; (3) 0854:46 - 0901:03 UT and (4) 0917:10 - 0924:00 UT. The division between burst 1 and 2 is somewhat arbitrary. It was placed where the 4.1-6.7 MeV nuclear excess flux begins to raise again after burst 1.

The 4.1-6.7 MeV nuclear de-excitation fluxes, the 2.2 MeV/ 4-7 Mev fluence ratios and the 2.2 MeV decay time constants, calculated by the above mentioned method are listed in Table 1.

According to column 4 of the table, the flare as a whole is very hard, but the 2.2 MeV to 4-7 MeV ratio of burst 3 is the highest value observed so far for a flare or a burst within a flare. The parent particle spectrum must have been

TABLE 1.

Burst no.	Time interval [UT]	ϕ(4.1-6.7 MeV) γ/cm^2	$\frac{\phi_{2.2MeV}}{\phi_{4-7MeV}}$	τ_e [sec]
1	0830:12-0835:56	63 ± 6	1.4 ± 0.15	105 ± 10
2	0835:56-0854:46	125 ± 15	1.8 ± 0.16	80 ± 5
3	0854:46-0901:03	65 ± 4	3.1 ± 0.2	70 ± 5
4	0917:10-0924:00	14 ± 3	2.5 ± 0.22	90 ± 10

extremely hard. This, however, only pertains to the lower energies, because otherwise the pion decay flux above 35 MeV would have been tremendously high, which contrasts our measurements. The particle spectrum, therefore, must have steepened at higher energies considerably. Burst 2, on the other hand, because of the high photon flux above 35 MeV suggests a hard particle spectrum up to high energies. To assess this we use the Mixed Matrix Element (MME) emission above 35 MeV. The photon flux is obtained by taking the effective area published (12). For bursts 2 and 3 we get a flux of 9 $\pm 3 \frac{\gamma}{cm^2}$ and 1.3 $\pm 0.6 \frac{\gamma}{cm^2}$, respectively. For bursts 1 and 4 only 1sigma upper limits of 0.3 and 0.34 $\frac{\gamma}{cm^2}$, respectively, can be given. These values are normalized to the 4.1- 6.7 MeV fluences and, assuming that the signal is pion decay flux only, compared to yield calculations provided by Ramaty 1995 for a Bessel-function spectral shape and a power law (figure 2). The energetic particle spectral parameter is obtained by inserting the fluence ratios listed in column 4 of the table into new fluence ratio calculations (13) carried out for two different elemental compositions and two different directionalities of the primary particles, assuming a thick target situation.

It is evident that the energetic particle spectrum is compatible with a Bessel-function distribution for bursts 1 and 3, independent of the composition. The same holds for burst 4, whose upper limits are not listed in Figure 2. This calls for a stochastic acceleration mechanism.

Burst 2 is exceptional, because the measurements suggest a particle distribution resembling a power law. Some of the most intense events recorded by the GRS on SMM showed phases with enhanced pion decay flux, as well, which point to a hard particle spectrum. These are the flares of 3 June 1982 (7) (8), 24 April 1984 (14) and 6 March 1989 (4). But in all these cases the (gradual) burst appears only at photon energies beyond 10 MeV, not at lower energies, and is preceeded by an intense primary burst, suggesting a two-phase scenario. Also some of the giant flares of June 1991 show this time profile (15). Contrary to this temporal history, the second burst of the 16 December 1988 flare is seen simultaneously from X-rays to high energy gamma-rays as a distinct event. The power law like spectrum deduced for the energetic particles may therefore be explained by a shock wave acting as a primary accelerating agent, a situation which seems to be rather exceptional. On the other hand, due to missing spatial resolution, we cannot exclude that burst 1 has served as a preaccelerator for the particles.

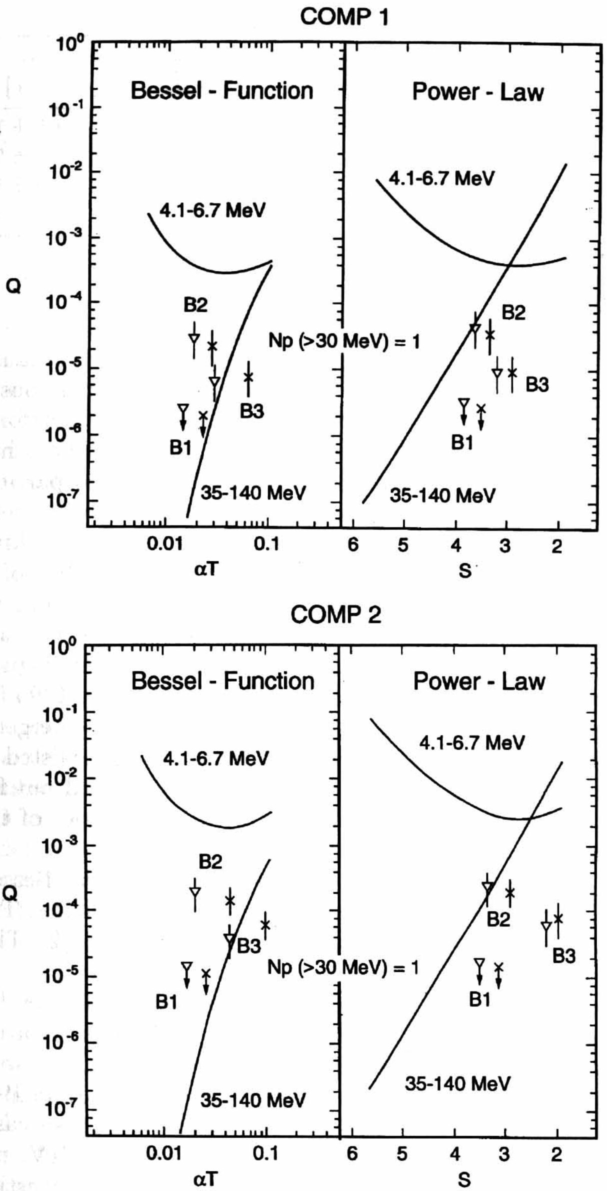

FIG. 2. Yield of the 4.1-6.7 MeV nuclear excess radiation and > 35 MeV flux resulting from pion decay versus the spectral parameters for a Bessel-function and a power law particle distribution (Ramaty, 1995, private communication) carried out for two different elemental compositions. The triangles and crosses mark the pion decay fluence normalized to the 4.1-6.7 MeV nuclear excess fluence of the bursts 1, 2 and 3 for, respectively, an isotropic downward and horizontal directionality of the primary particles.

CONCLUDING REMARKS

That a solar flare, which is extended in time, exhibits spectral variations is no surprise. But it is of interest to note how dramatic the changes are from burst to burst for this flare, even suggesting the action of different acceleration mechanisms. The present investigation once more demonstrates the importance to observe Solar flares with detectors sensitive in a wide energy range. Then insight into the phenomenon of particle acceleration can be gained which is out of the reach of particle detectors in space.

ACKNOWLEDGEMENTS

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