"EXTENDED PHASE" OF SOLAR FLARES OBSERVED BY *SMM*

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ABSTRACT

Throughout the 10-year operating history of the *SMM* Gamma-Ray Spectrometer (GRS), only a handful of large solar flares have exhibited measurable emission of neutral pions (through pion-decay γ–rays) or high-energy neutrons (detected at the Earth). For 4 of the flares in which neutral pion-decay γ-rays have been detected by GRS, most of the neutral pions appear to have been produced after the "main" impulsive phase as determined from hard X-rays and low–energy γ–rays. The time history of the γ–ray emission above 10 MeV during this "extended" phase is also strikingly similar from flare to flare. Similar time histories have also been seen by EGRET and Comptel on CGRO. This may mean that the acceleration of protons to high energy , or, alternatively, the precipitation of trapped high-energy particles, in an "extended" or "delayed" phase may be a common feature of flares with significant production of pions and high–energy neutrons. The extended phase emission can be characterized by exponential "decay" times of a few minutes. The relaxation time can apparently be much longer for flares strong enough to have sufficient counting statistics and for sufficient observing time.

SMM/GRS OBSERVATIONS

The flare observations reported here were made with the Solar Maximum Mission Gamma–Ray Spectrometer (*SMM*/GRS), which operated between 1980 and 1989. The primary GRS data were from an array of 7 NaI(Tl) scintillation detectors, each 7.6 cm in diameter by 7.6 cm thick. These detectors produced high–resolution (476 channel) spectra covering the energy range from 0.3 to 9 MeV with an accumulation time resolution of 16 s. The GRS also had a high–energy mode (HEM) consisting of a matrix of counts made up of energy–loss bins from interactions in two detector layers: the NaI(Tl) scintillator array and/or a 7.5 cm thick CsI(Tl) rear shield. The HEM covered an energy loss range of 10 to 100 MeV in 4 channels for each layer with a time resolution of 2 s. The GRS and its high–energy mode has been described in detail by Forrest *et al.* [1]

An important property of the HEM is its ability to discriminate, at least on a statistical basis, between γ–ray and neutron fluxes incident on the detector.[2,3] Basically, the incident γ–ray and neutron fluxes are determined when the fluxes are deconvolved from the count matrix. The separation depends on the fact that multiple events (*i.e.* coincident interactions in both the NaI and CsI layers) are produced almost exclusively by γ–rays, while neutrons produce mainly singles events (*i.e.* interactions in the NaI or CsI, but not both). This characteristic of the HEM has been quantified by Monte Carlo calculations[4] and accelerator tests of a layered detector.[5]

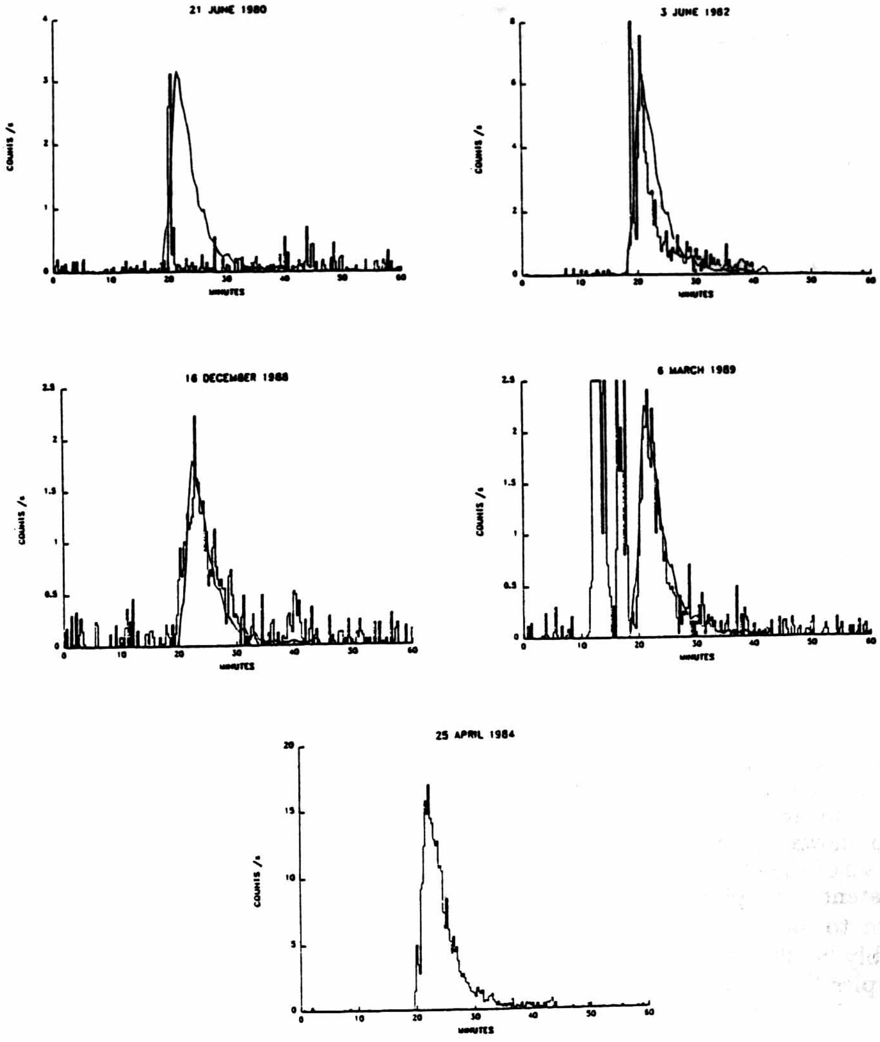

Figure 1. Time histories for 5 flares in the GRS HEM "multiples" channel for energy loss > 25 MeV. This channel is sensitive to high–energy γ–rays. The vertical axes are scaled and the time axis aligned to emphasize the similarity of a time–extended feature in some of the flares. A scaled and smoothed envelope of the 1984 April 24 flare is overlayed on the data from the other flares. All but the flare of 1980 June 21 show strong evidence of pion production.

Table 1
Parameters for bursts of "extended" high–energy emission (>25 MeV).

Flare Date	GOES/H_α	Position	c_1 ($[16\ \mathrm{s}]^{-1}$)	τ_1 (min)	c_2 ($[16\ \mathrm{s}]^{-1}$)	τ_2 (min)	χ^2/ν	ν
82/6/3	X8/2B	S09E71	108.1±8.2	1.15±0.14	17.1±3.9	11.7±3.0	0.96	68
84/4/25	X13/3B	S12E43	321.2±7.6	3.23±0.07	2.2±1.2	≥ 10	1.28	76
88/12/16	X4.7/1B	N27E33	30.5±2.7	3.34±0.30	-	-	0.75	53
89/3/6	X15/3B	N35E69	36.7±3.3	2.66±0.27	-	-	0.65	41

ν is the number of degrees of freedom for the fit.

Results of GRS observations of high–energy (> 10 MeV) photons and neutrons have been reported previously for the flares of 1980 June 21,[3,6] 1982 June 3,[3,7] 1988 December 16,[8] and 1989 March 6.[9,10] All of these flares have produced high–energy neutrons with sufficient intensity to be seen by the GRS HEM. In addition, ground level neutron monitors responded to flare neutrons > 1 GeV on 1982 June 3 [11] and protons from the decay of flare neutrons were also observed from this flare. [12]

Figure 1 shows the background–subtracted "light curves" from the GRS HEM multiple events for these flares. Since the multiple events are insensitive to neutrons, these plots give the time history of flare photons (> 25 MeV). Previous studies[3,8,9] have shown that the bulk of the pion production during these flares takes place after the x–ray and γ–ray onset during a "delayed" or "extended" phase. Although the light curves at the onset can be quite different (compare December 16 and March 6), the similarity among the light curves during the time intervals of enhanced pion production is striking. Figure 1 also shows the time history for the flare of 1984 April 24/25. A preliminary analysis of the GRS HEM data for this flare shows an extremely hard spectrum, consistent with pion decay, over a period of ~ 25 minutes. This flare is also known to have produced neutrons in the energy range 20 to 200 Mev[12] and possibly > 400 MeV.[13] In what follows, we assume that the 1984 April 24 HEM multiples light curve is dominated by pion–decay γ–rays.

TIME HISTORIES OF THE "EXTENDED PHASE"

Motivated by the analysis of the 1991 June 11 flare by Kanbach *et al.*,[14] where the > 30 MeV γ–rays showed an exponential decrease with time, and by the similarity among the time histories of the GRS high–energy flares, we have fit the time histories with an exponential decay model. The model is of the form

$$C(t) = c_1 e^{-(t-t_0)/\tau_1} + c_2 e^{-(t-t_0)/\tau_2}.$$

The results of the fitting are listed in Table 1. In the case of the flares of 1988 December 16 and 1989 March 6, a single exponential was sufficient to fit the decreasing part of the γ–ray light curve. For the 1982 June 3 flare, a sum of two exponentials was needed for an acceptable fit to the data. For the 1984 April 24

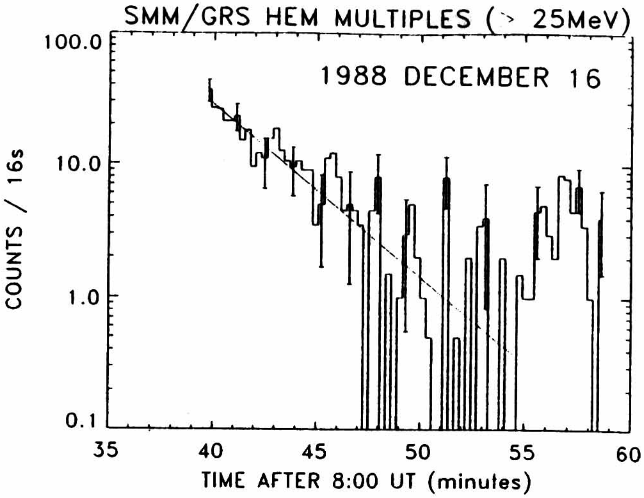

Figure 2. Time history of GRS HEM multiples events for the decreasing part of the 1988 December 16 flare. A single exponential is used to fit this part of the light curve. Selected error bars, based on counting statistics, are shown.

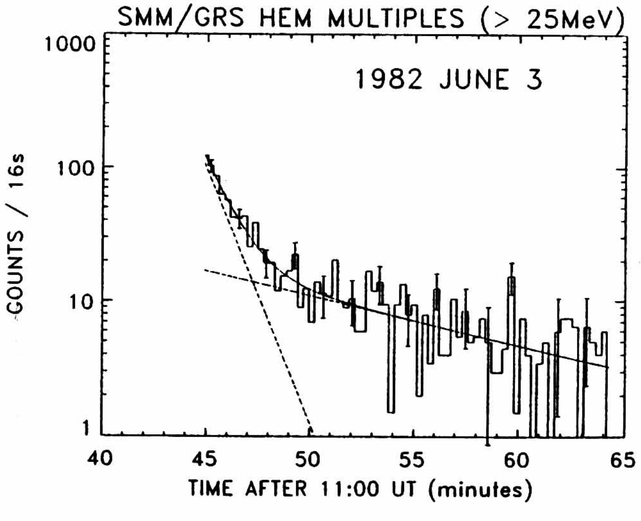

Figure 3. Time history of GRS HEM multiples events for the decreasing part of the 1982 June 3 flare. Two exponentials are used to fit this part of the light curve. The two components are shown by dashed lines, the sum of the components by a solid line. Selected error bars, based on counting statistics, are shown.

flare, the addition of a second exponential significantly improves the fit (from a probability of exceeding χ^2 of 0.01 to 0.10); however, the decay time of the second exponential is poorly determined because of limited counting statistics late in the flare and because the data was terminated at satellite nightfall. In all cases, the rise time is $\sim$ 2 minutes to reach maximum intensity. Figures 2 and 3 show the fits for two of the flares.

It should be noted that subsequent bursts of γ–rays can have the effect of lengthening the apparent decay time of an earlier burst. Only in the case of the 1988 December 16 flare, however, do we clearly see the effect of a later burst. But here the burst (which occurs near minute 56 in Figure 2) comes late enough to be excluded from the data used in the fit. Since the exponential fits give formally acceptable χ^2 (probability of exceeding $\chi^2 \geq 0.1$ in all cases), it appears that secondary bursts do not make significant contributions to the light curves. The fact that the flares of 1988 December 16 and 1989 March 6 do not show the more extended decay times of the 1982 June 3 and 1984 April 24 flares could be a selection effect caused by the relatively lower flux from the former flares.

CONCLUSIONS

This comparison of 4 large flares observed by the *SMM*/GRS shows that pion–decay photons were produced in a time–extended phase. This phase can be characterized by an exponential decay or relaxation time. This time is at least of the order of several minutes. The largest flares, with the best counting statistics and sufficiently long observation times, have a component that can last more than 10 minutes and perhaps much longer. This behavior is similar to the very long duration emission from the 1991 June 11 flare reported by Kanbach *et al.* [14] In that case, the sensitivity of the EGRET detectors allowed a significant flux to be observed up to 8 hours after flare onset. Ryan *et al.* [15] have observed time-extended production ($\sim$ 10 minutes) of solar flare neutrons from the flare of 1991 June 9. This neutron production was taken as evidence for significant hardening of the proton spectrum over this period. Time–extended emission of γ–rays from pion decay has also been reported by Akimov *et al.*[16,17] for the flare of 1991 June 15. Finally, high–energy γ–ray emission detected by EGRET's NaI spectrometer from a number of flares during 1991 June has been described by Schneid *et al.* [18] These events also exhibited long–duration emission with a component consistent with pion decay.

There can be significant production of pions during the initial burst, for example on 1982 June 3.[3] However, from the above observations there is clear, if only circumstantial, evidence for an association between copious pion production and a time–extended phase of flares. From the *SMM* data alone, in all 4 flares for which there is strong evidence for pion–decay γ–rays, the pion production takes place mainly during a burst over a time scale of minutes or more. Since pion production is the result of interactions of protons with kinetic energies > 300 MeV, it follows that the acceleration of protons to these energies (or at least their transport to interaction regions) takes place over this time scale.

The decay–like profile which seems to be characteristic of these events probably reflects a process or morphology common to the flares. One likely possibilty is particle trapping and pitch angle scattering in flare loops (*e.g.* Mandzhavidze and Ramaty[19]). This would explain the decay of the radiation, with the decay time depending on the loop's size, shape, and location, and the amount of plasma turbulence in it. Another question is whether significant proton acceleration to > 300 MeV takes place during this extended phase.[20,21,22] This could be addressed by looking for changes in the proton spectral shape during the event using ratios of γ–ray line fluxes and the neutral–pion–decay γ–ray flux.[23] Given the high sensitivity of the Compton GRO detectors, it is likely that a much larger sample of flares with a detectable extended phase will become available for the relevant studies.

ACKNOWLEDGMENTS

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REFERENCES

1. Forrest, D.J., *et al.*, Solar Phys. **65**, 15 (1980).
2. Chupp, E.L., *et al.*, Proc. 19th Int. Cosmic Ray Conf. **4**, 126 (1985).
3. Forrest, D.J., *et al.*, Proc. 19th Int. Cosmic Ray Conf. **4**, 146 (1985).
4. Cooper, J.F., *et al.*, Proc. 19th Int. Cosmic Ray Conf. **5**, 474 (1985).
5. Dunphy, P.P., *et al.*, Experimental Astron. **2**, 233 (1992).
6. Chupp, E.L., *et al.*, Ap. J. (Letters) **263**, L95 (1982).
7. Chupp, E.L., *et al.*, Ap. J. **318**, 913 (1987).
8. Dunphy, P.P., and Chupp, E.L., in Particle Acceleration in Cosmic Plasmas, ed. G. Zank and T.K. Gaisser (AIP, N.Y., 1992), p. 253.
9. Dunphy, P.P., and Chupp, E.L., Proc. 22nd Int. Cosmic Ray Conf. **3**, 65 (1991).
10. Rieger, E., and Marschhäuser, H., Proc. of MAX '91 Workshop # **3**, ed. R.M. Winglee and A.L. Kiplinger (U. Colorado, Boulder CO, 1990), p. 68.
11. Debrunner, H., Flückiger, E., Chupp, E.L., and Forrest, D.J., Proc. 18th Int. Cosmic Ray Conf. **4**, 75 (1983).
12. Evenson, P., Kroeger, R., Meyer, P., and Reames, D., Ap. J. (Supplement) **73**, 273 (1990).
13. Smart, D.F., Shea, M.A., Flückiger, E.O., Debrunner, H., and Humble, J.E., Ap. J. (Supplement) **73**, 269 (1990).
14. Kanbach, G., *et al.*, A & AS, in press (1993).
15. Ryan, J., *et al.*, presented at IAU Colloquium #142, College Park, MD, Jan. 11–15 (1993).
16. Akimov, V.V., *et al.*, Proc. 22nd Int. Cosmic Ray Conf. **3**, 73 (1991).
17. Akimov, V.V., *et al.*, these proceedings (1993).
18. Schneid, E.J., *et al.*, these proceedings (1993).
19. Mandzhavidze, N., and Ramaty, R., Ap. J. (Letters) **396**, L111 (1992).
20. Debrunner, H., Flückiger, E.O., and Lockwood, J.A., Ap. J. (Supplement) **73**, 259 (1990).
21. Ryan, J.M., and Lee, M.A., Ap. J. **368**, 316 (1991).
22. Forrest, D.J., these proceedings (1993).
23. Murphy, R.J., and Ramaty, R., Adv. Space Res. **4** (7), 127 (1985).