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OBSERVATIONS WITH THE *SMM* GAMMA-RAY SPECTROMETER: THE IMPULSIVE SOLAR FLARES OF 1980 MARCH 29

J. M. RYAN, D. J. FORREST, E. L. CHUPP, AND M. L. CHERRY
University of New Hampshire, Durham, New Hampshire

C. REPPIN, E. RIEGER, K. PINKAU, AND G. KANBACH
Max Planck Institute for Physics and Astrophysics, Munich, Germany

AND

G. H. SHARE, R. L. KINZER, M. S. STRICKMAN, W. N. JOHNSON, AND J. D. KURFESS
Naval Research Laboratory, Washington, DC
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ABSTRACT

Gamma-ray continuum emission from 0.3 to ~1 MeV was observed with the Gamma-Ray Spectrometer on the *Solar Maximum Mission* satellite during two impulsive solar flares on 1980 March 29, from active region 2363 at 0918 UT and from active region 2357 at 0955 UT. Evidence is presented for a hardening of the spectrum during the impulsive phase of the flares. The photon intensity >100 keV appears to decay at a slower rate than that at lower energies. Time-integrated photon spectra for both flares are incompatible with a single-temperature thermal-bremsstrahlung model. Upper limits for prompt and delayed γ-ray lines are presented.

Subject headings: gamma rays: general — Sun: flares

I. INTRODUCTION

Nuclear line and continuum γ-ray emission from solar flares have been observed up to several MeV (Chupp *et al.* 1973; Chupp, Forrest, and Suri 1975; Gruber, Peterson, and Vette 1973; Suri *et al.* 1975; Chambon *et al.* 1979; Hudson *et al.* 1980). As summarized by Ramaty (1980), the spectral characteristics and time histories of these emissions yield information concerning solar flare particle acceleration and the environment in the flare region.

On 1980 March 29 significant flare activity was observed between 0900 UT and 1000 UT. Two impulsive bursts with durations <20 s were observed by the Gamma-Ray Spectrometer with emissions extending to photon energies in excess of 500 keV. The time structure of each of the bursts was relatively simple and resembles the shape of the individual bursts observed during the multiburst phase of a complex γ-ray–emitting flare observed on the *SMM* satellite (Chupp *et al.* 1981). The two events we discuss here may, therefore, provide a view of a more elementary form of a high-energy γ-ray flare.

The Gamma-Ray Spectrometer (GRS) has been described previously by Forrest *et al.* (1980) and consists of seven 7.6 × 7.6 cm NaI(Tl) crystals operating in the energy range from ~0.3 to 9 MeV. The combined energy resolution of the seven crystals of the spectrometer is 7% at 662 keV. Two 8 cm^2 auxiliary hard X-ray detectors are incorporated in the experiment. They operate in the approximate ranges 10–80 keV (detector X1) and 10–140 keV (detector X2). X-ray data are accumulated in four pulse height channels every 1.024 s, while the γ-ray data are accumulated in 476 channels every 16.38 s. A single-channel *burst window* in the GRS provides 64 ms time resolution in a 50 keV band centered at 330 keV.

II. OBSERVATIONS

a) Continuum

The impulsive phase of flare 1 occurred in AR 2363 (Boulder series) at 0918 UT and was classified as a C9.6 X-ray event. The impulsive phase of flare 2 occurred in AR 2357 at 0955 UT and was optically classified as SB by the Athens Solar Observatory; it was classified as M1.9 in the X-ray band. Ground-based and other observations of flare 1 are discussed by Rust *et al.* (1981), Dennis, Frost, and Orwig (1981), Acton *et al.* (1981), and Culhane *et al.* (1981). Both events were seen in all eight of the X-ray channels (10–140 keV) and in several low-energy channels of the GRS (<1 MeV). It is instructive to discuss these flares together because of their similarities, even though they originate in different nearby active regions.

Shown in Figures 1*a* and 1*b* are count rate time profiles for X-ray channels covering the 25–140 keV range and the *burst window* (305–355 keV), plotted with a time resolution of 2 s, for flares 1 and 2, respectively. The qualitative temporal features exhibited at different energies from 25–355 keV are similar. For example, in flare 1 an *e*-folding rise time of 2.9 ± 0.2 s is consistent with all the data. Dennis, Frost, and Orwig (1981) have made a higher time resolution analysis of the hard X-ray data (25–380 keV) from flare 1 using the Hard X-Ray Burst Spectrometer (HXRBS) on *SMM*. They report intensity changes on time scales of ≤ 1 s. Time structure on the order of 1 s is also evident in our data but is not plotted here.

The data in Figure 1 suggest that the duration of each burst is longer at energies >300 keV than at lower energies. This is evident in the time behavior of the spectral hardness ratios [or background-corrected intensity ratios (305–355 keV)/(40–140 keV)], which are plotted at the top of the figures. The average hardness ratio prior to the peak of the burst is lower than that after the peak by 2.3 σ for flare 1 and by 2.9 σ for flare 2. Additional evidence for spectral hardening during flare 1 is found by comparing the number of counts (background corrected) greater than 275 keV in the 16.4 s prior to the peak of the flare with those in the 16.4 s after the peak. We find a 48% increase, 2 σ, with time from the 358 $\pm$ 57 counts observed before the peak to the 530 $\pm$ 58 observed after the peak. During the same time interval, the 40–80 keV integrated counts decreased by $\sim$23% from 4001 to 3087. There is evidence for spectral hardening in the GRS data for flare 2 in addition to that mentioned above. In particular, we observe a 4.9 σ residual flux over background, for energies >275 keV, during the 25–74 s after the peak of the X-ray emission. During this same time interval, the X-ray rate has returned to its background level.

The γ-ray spectrum for flare 1 integrated over 32.8 s is plotted in Figure 2. No single-temperature thermal-bremsstrahlung spectrum adequately describes the GRS data from 275 keV to 1 MeV. This is due to the flatness of the spectrum >300 keV. A fit through only the data above 400 keV requires a temperature (kT) in excess of 500 keV. A power law with a spectral index of ~ -4.2 adequately fits all GRS data above 275 keV. The spectral data from the GRS for flare 2 covering the 16.4 s interval which includes the peak phase, is shown in Figure 3. Again a power law with exponent ~ -4.4 adequately fits the data above 275 keV. We have chosen to plot in Figures 2 and 3 only the full γ-ray flare spectrum of the GRS since there are inconsistencies in energy calibration between HXRBS

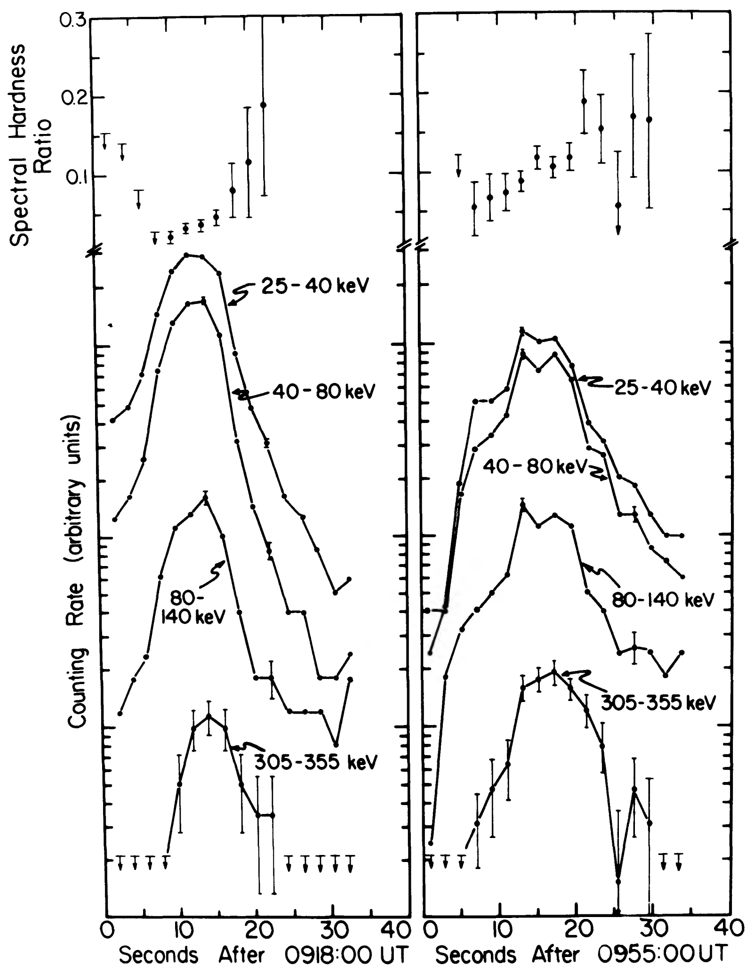


FIG. 1.—(*a*) Flare 1 and (*b*) flare 2 count rate time profiles are shown for selected X-ray channels and tne γ-ray *burst window*. The reader should not interpret the relative scaling of the different count rate curves as being due to count rate magnitude differences. The individual curves are plotted together merely as a visual aid. The corrected count rate ratio of the *burst window* (305–355 keV) to the X-ray channels (40–140 keV) is plotted on a linear scale as the spectral hardness ratio at the top of the figure.

and the X-ray detectors on GRS which do not allow, at this time, for direct comparison of data below the threshold of our spectrometer (275 keV). However, the GRS, with a time resolution of 16.4 s, has inflight gain stabilization and calibration which is consistent with the preflight calibration to less than 1%.

b) Discrete Gamma-Ray Lines

We have searched the GRS spectral data shown in Figures 2 and 3 for evidence of γ-ray line features. No features have been found. We set upper limits to prompt lines at 4.4 (^{12}C) and 6.1 MeV (^{16}O) in both flares and limits on delayed lines at 0.51 MeV (e^+ annihilation) and 2.2 MeV (neutron capture on hydrogen) for flare 1. The second flare occurred too close to sunset for the delayed lines to be studied. These limits are given in Table 1.

III. DISCUSSION AND SUMMARY

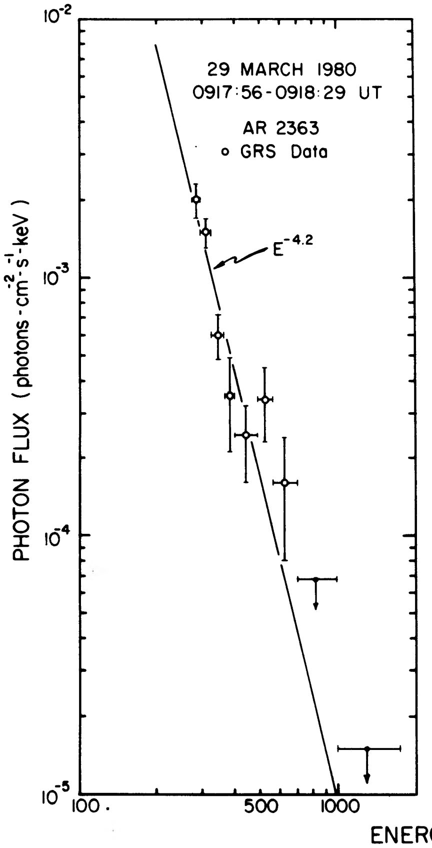
The progressive hardening of the spectrum, above 275 keV, during the two flares on 1980 March 29 is apparently due to the slower rate of decline for the higher-energy photon emission relative to that at lower energies. It is not due to a slower rate of rise at high photon energies because the rise times in several energy bands from 10–350 keV agree with one another to within $\sim$2 s. This differs from the $\sim$10 s delay in peaking at high photon energies observed in the 1972 August 4 flare (Hoyng, Brown, and van Beek 1976; Benz 1977). Bai and Ramaty (1979) have attributed this delay to electron trapping followed by a second stage of acceleration producing photons $>$100 keV.

Our evidence for the slower decline in the emission at high energies can be represented by fitting *e*-folding decay times to the rates observed at low and high energies. In particular for flare 2, at energies $<$140 keV, this fitted decay time is 2.6 $\pm$ 0.2 s, whereas at $\sim$350

TABLE 1

2 σ Upper Limits to γ-Ray Line Fluxes

Type of Line	E(MeV)	Flare 1 (γ cm^{-2} s^{-1})	Flare 2 (γ cm^{-2} s^{-1})
Delayed........	0.51	1.1×10^{-2}	...
	2.223	4.3×10^{-3}	...
Prompt........	4.4	8.3×10^{-3}	1.4×10^{-2}
	6.1	2.2×10^{-2}	2.2×10^{-2}



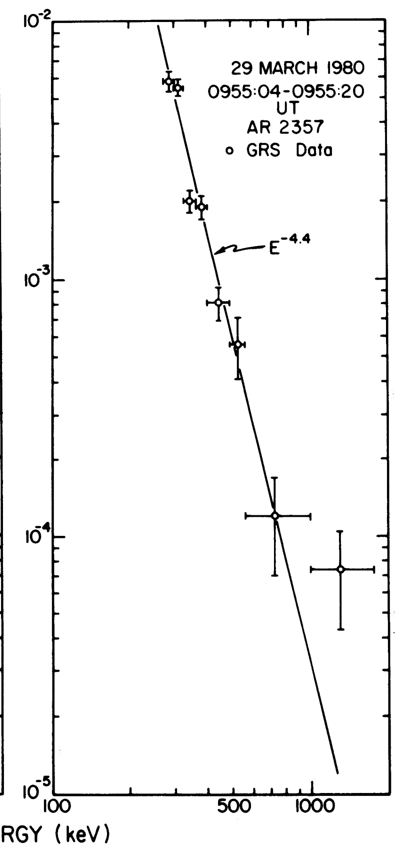


Fig. 2   Fig. 3

Fig. 2.—The spectral data from the Gamma-Ray Spectrometer are shown for flare 1 for the time interval 0917:56–0918:29 UT.

Fig. 3.—The spectral data from the Gamma-Ray Spectrometer are shown for flare 2 for the time interval 0955:04–0955:20 UT.

keV, it is 7.5 ± 3.0 s. In an electron-trapping model interpretation, this range of *e*-folding X-ray flux decay times, <140 keV, in the impulsive phase indicates densities of approximately 10^8 cm^{-3} if the decay is driven by electron collisional losses (Trubnikov 1965; Ginzburg and Syrovatskii 1964). The relatively longer decay times at the higher energies after the impulsive phase imply densities of about 5×10^8 cm^{-3}. These results are consistent with electron acceleration taking place at relatively low densities and with the high-energy electrons propagating to regions of increasing density before they are stopped. However, we cannot strictly rule out a second-stage acceleration process with a much less intense, but harder, spectrum than the main impulsive burst as a source of the spectral hardening.

It is interesting to compare the intensity of γ-ray line emission observed in a larger flare with the upper limits obtained for line emission for the two flares on 1980 March 29. We find that the upper limit to the intensity of the 2.23 MeV line from flare 1 is at least a factor of 2 lower than the observed intensity of this line during the 1972 August 4 flare when both observations are normalized to the continuum emission at 300 keV. From this it appears that ion acceleration took on greater importance relative to electron acceleration during the latter flare.

In summary, two impulsive solar flares on 1980 March 29 produced γ-rays above 500 keV. Only upper limits were obtained for the presence of narrow γ-ray lines produced by energetic ions. Thus, the full energetic photon spectrum could be due to electrons whose spectra extend to relativistic energies. These γ-ray events were associated with flares which are relatively small by both optical and soft X-ray standards and exhibit several interesting characteristics:

1. The γ-ray emission from flare 1 and 2 was detected primarily during the time of the impulsive phase of these flares.
2. The photon emission, ~300 keV and above, from both flares showed a relative enhancement and prolonged time behavior in the later stages of the impulsive phase as compared to the emission at lower energies.
3. The total emission cannot be adequately described by a single-temperature thermal-bremsstrahlung function for either event. This discrepancy grows during the later stages of each flare.

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M. L. Cherry: University of Pennsylvania, Department of Physics, Philadelphia, PA 19104

E. L. Chupp, D. J. Forrest, and J. M. Ryan: University of New Hampshire, Department of Physics, Durham, NH 03824

W. N. Johnson, R. L. Kinzer, J. D. Kurfess, G. Share, and M. Strickman: Naval Research Laboratory, 4555 Overlook Avenue, S.W., Washington, DC 20375

G. Kanbach, K. Pinkau, C. Reppin, and E. Rieger: Max Planck Institute for Physics and Astrophysics, Institute for Extraterrestrial Physics, 8046 Garching, Federal Republic of Germany