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GAMMA-RAY PRECURSORS OF SOLAR FLARES

E. RIEGER
Max-Planck-Institut für Extraterrestrische Physik, 8046 Garching, Germany
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ABSTRACT

Bursts have been observed by the gamma-ray spectrometer on *SMM* at medium- and high-energy gamma-rays that precede the flare maximum. The negligible contribution of nuclear lines in the spectra of these events and their impulsive appearance suggests that they are hard-electron–dominated events superposed on the flares. Spatial resolution at gamma-ray energies will be necessary to decide whether this kind of bursts is cospatial with the flares or whether they occur in the flares' vicinity.

Subject headings: Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

By analyzing the temporal history of solar flares it is frequently observed that the peak in different energy bands does not occur at the same time. The emission at medium-energy X-rays ($\gtrsim$30 keV) caused by bremsstrahlung of subrelativistic electrons is usually leading the output at higher energies. Very impulsive events show delays between X- and gamma-rays of zero to several seconds, whereas gradual and long duration events exhibit delays of order 1 minute (Forrest & Chupp 1983; Yoshimori et al. 1983; Kane et al. 1986; Vlahos et al. 1986; Rieger 1991). These delays have been interpreted in various ways. The two most popular models are (1) a two-step or two-stage scenario, where the delay of the high-energy emission is explained by a second-step that accelerates electrons to relativistic energies and protons to energies of $\approx$10 MeV and more, initiated by a first step, the impulsive burst (see, e.g., Bai & Ramaty 1979; Bai & Dennis, 1985), and (2) a partial trapping and/or propagation model, where delays result from partial trapping and/or propagation effects that electrons and protons (ions) suffer in their transport from acceleration to the hard X-ray– and gamma-ray–emitting regions (see, e.g., Vilmer, Kane, & Trottet 1982; Hulot, Vilmer, & Trottet, 1989; Hulot et al. 1992).

There are, however, some flares observed by the Gamma-Ray Spectrometer (GRS) on *SMM* with temporal peculiarities that cannot be explained by either of the above-mentioned models. In the course of these events, bursts, apparent in the nuclear energy range (4–7 MeV) and at energies above 10 MeV, were recorded that clearly precede the flare maxima evidenced in hard X-rays. These bursts are especially prominent in the GRS energy range 10–25 MeV. We therefore name them gamma-ray precursors.

In this paper we show the temporal history of these events and by considering their spectral characteristics make an attempt to explain these flare anomalies.

2. OBSERVATIONS

The flares that contain gamma-ray precursors in their temporal history belong to the relatively rare case of events with intense emission above 10 MeV. They are listed in Table 1.

The X-ray class, optical importance, flare location, and active region number (AR) have been taken from the *Preliminary Report and Forecast of Solar Geophysical Data,* published by NOAA.

The flare of 1981 October 14 was recorded shortly before *SMM* went into occultation (Rieger 1982). However, *Hinotori* observations reveal that the GRS saw the main part of the event (Yoshimori 1990). It is shown in Figure 1 in different energy intervals. At gamma-ray energies, especially in the energy range 10–25 MeV, there appear two bursts for which a significant counterpart at the high-energy X-rays is lacking. Bursts one and two (indicated by vertical dotted lines) precede quite clearly a shoulderlike feature and the flare maximum at X-ray energies, respectively.

The flare of 1982 June 3 due to its enormous power in emitting high-energy photons and particles, has been intensively investigated (see, e.g., Chupp 1990a). Little attention, however, has been paid to the temporal evolution before the first intense maximum. In Figure 2 the premaximum time history is shown at X- and gamma-ray energies. Similar to the flare described above, two bursts occur at medium- and high-energy gamma rays for which a counterpart at the X-rays is missing.

The flare of 1983 May 7, whose time history is shown in Figure 3, exhibits a burst on the rising part of the emission (Rieger 1989). It is again most apparent in the energy band 10–25 MeV and lacks a significant counterpart at X-ray energies.

The information we can get from the spectra of these events is curtailed by the fact that the temporal resolution of the GRS for a spectrum between 0.3 and 9 MeV is ~16 s. Fortunately, however, all the events happened to occur in one spectral time interval. This minimizes the "contamination" by nonburst emissions. It is found that the spectra are continua without the evidence for nuclear lines. They flatten around 1 MeV but do not show an intensity drop above ~7 MeV, which is a characteristic of line events (Rieger 1991). The second burst of the 1982 June 3 flare, however, is somewhat exceptional to this. Although continuum dominates the spectrum, the lines of ^{12}C and ^{16}O at 4.4 and 7.1 MeV, respectively, are apparent.

3. DISCUSSION AND CONCLUSION

The poor evidence for nuclear interactions in the spectra of these gamma-ray precursors rules out high-energy protons as

TABLE 1

FLARES WITH GAMMA-RAY PRECURSORS

Date	Time (UT)	*GOES* Class Importance	Active Region	Heliographic Position
1981 Oct 14	2218	X 3.1/2B	4171	S30 E67
1982 Jun 3	1142	X 8.0/2B	3763	S09 E72
1983 May 7	1705	X 3.0/SB	3406	S06 E88

the source of the emission in the energy range 4.1–6.4 MeV. This liberates us from the need to explain how protons are accelerated before the electrons (which cause the X-ray emission), or in case of simultaneous acceleration of protons and electrons, how protons dump their energy faster than electrons. We then, however, have to explain, why these events do not show a significant counterpart at X-ray energies. Because the flares occurred close to the solar limb, the question arises if the X-rays could have been absorbed in the high line-of-sight column density of the solar atmosphere. Calculations have shown that ≈200 keV photons emitted from chromospheric heights, are attenuated considerably only, in case they originate slightly behind the limb (Vestrand et al. 1987). For events observed before the limb, the absorption of high-energy X-rays should be small, even if the radiation comes from footpoints as low as ≈500 km above the photosphere.

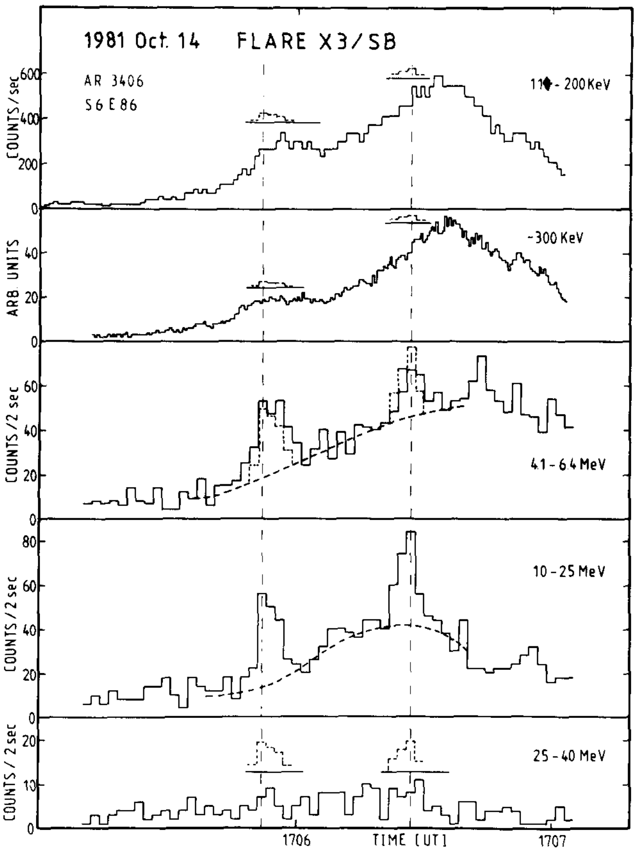

FIG. 1.—Temporal history of the 1981 October 14 flare in different energy bands. The dashed lines in the energy channels 4.1–6.4 MeV and 10–25 MeV indicate how the separation between the flare and the burst emission was made. Shown by dotted histograms in the lower energy channels is the calculated flux by using the 1989 March 6 flare from 1358:04–1358:12 UT as a spectral templet (approximate energy dependence between 100 keV and 25 MeV is E^{-2}).

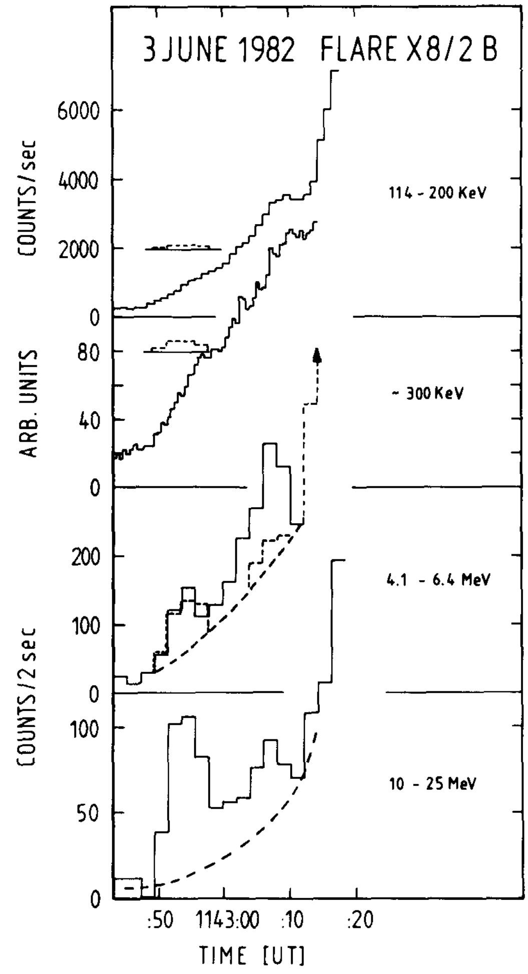

FIG. 2.—Temporal history of the 1982 June 3 flare before the main intense flare maximum.

Because of the spectral characteristics mentioned, and the impulsive appearance, we adopt the working hypothesis that the gamma-ray precursors are electron dominated events, superposed on the output of the flares. Events of this type were discovered as a subset of GRS flares with photon emission greater than 10 MeV (Rieger & Marschhäuser 1990). They are called "electron dominated," because continuum emission originating from electron bremsstrahlung dominates their spectra, the contributions from line radiation being negligible. They are generally of an impulsive nature and do not show a delay between X-rays and the emission in the energy range 4.1–6.4 MeV and above 10 MeV within the detector's time resolution (2 s). Because their spectra are hard, they appear most clearly in the GRS energy range of 10–25 MeV. We can estimate the output of the gamma-ray precursors at X-ray energies if we use the first burst of the 1989 March 6 flare—a prototype of a hard-electron-dominated event (Rieger & Marschhäuser 1990; Chupp 1990b; Marschhäuser 1993)—as

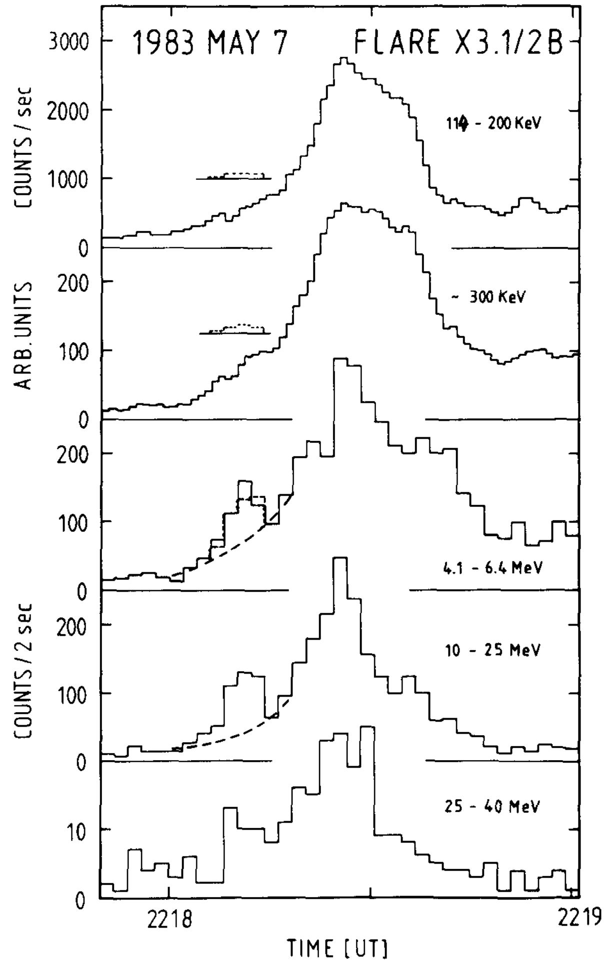

FIG. 3.—Temporal history of the 1983 May 7 flare

a spectral templet and normalize the fluxes at 10–25 MeV. The thus calculated flux at lower energies is indicated in the figures by dotted histograms. We see that at 4.1–6.4 MeV the observed and calculated emissions agree relatively well (except the second burst of the 1982 June 3 flare). It turns out, however, that the calculated X-ray signal is too low to appear in the ongoing X-ray emission of the flares.

These events have many features in common to hard cosmic gamma-ray bursts: the bursty appearance, the lack of gamma-ray lines and the low emission at X-ray energies (Rieger et al. 1982; Share et al. 1986, 1991). It is, therefore, appropriate to estimate the probability that these gamma-ray precursors of solar flares are chance coincidences of a hard cosmic gamma-ray burst and a solar flare. The GRS on *SMM*, during its 4.3 year overall lifetime for solar observation, recorded 26 solar flares and 11 cosmic gamma-ray bursts with emission above 10 MeV. The probability that a flare and a burst coincide within a time interval of 2 minutes is given by

$$P = 120\text{ s}\left[\frac{26 \times 11}{(1.36 \times 10^8\text{ s})^2}\right] \times (1.36 \times 10^8\text{ s}) = 2.5 \times 10^{-4} \quad (1)$$

Taking into account that the flares with emission larger than 10 MeV were more frequent from mid-1981 to mid-1983 (the period in which these events occurred) than averaged over the whole measurement time, the probability increases by about a factor of 2. It is therefore rather unlikely that these events are the result of a chance coincidence between flares and cosmic gamma-ray bursts with emission above 10 MeV.

The discussion has shown that the temporal and spectral peculiarities of the gamma-ray bursts can be explained most easily if we assume that they are hard-electron-dominated events, superposed on the flares. According to our observations, they tend to precede in time the flare maxima. Electron-dominated events are apparently more frequent than originally estimated (Rieger & Marschhäuser 1990). They have been observed on other detectors in space, too, for instance by SIGMA on *GRANAT* (Pelaez et al. 1992; Vilmer 1993), by the WBS on *Yohkoh* (Yoshimori et al. 1993; Yoshimori 1993), and possibly also by *Hinotori* (Yoshimori, Okudaira, & Yanagimachi, 1986). Spatial resolution at gamma-ray energies as proposed in the HESP project will be necessary to decide whether these events are cospatial with the main flare or occur at different locations.

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