Temporal fine structure in hard γ radiation in solar flares

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The time evolution of the γ radiation with an energy above 30 MeV from two powerful solar flares (26 March and 15 June 1991) has been measured and analyzed. The radiation was detected by the GAMMA-1 orbiting telescope. The γ flare of 26 March consisted of a main burst lasting 11 s and several weaker bursts repeating at intervals from 10 s to several minutes. A fine structure is observed in the bursts. It consists of isolated radiation peaks with a time scale of 0.1–0.3 s. It is suggested that the temporal structure of a γ-ray burst corresponds to discrete particle-acceleration events during the solar flare and, possibly, to a bunching of accelerated beams. The time evolution of the flare on 15 June, with a duration ~ 2 h, also shows evidence of discrete radiation bursts.

The traditional methods of observing solar flares, which use ground-based optical and radio telescopes, have recently been supplemented by methods based on x-ray and γ-ray detectors on board satellites and orbiting stations. The latter approach is attracting increasing interest. A goal of the research in this hard radiation is to clarify the role played by nuclear processes in flares, the particle acceleration mechanism, and the mechanism for the interaction of accelerated beams with the solar atmosphere. A large number of flares accompanied by γ radiation have been detected[1,2] by the SMM satellite in the γ-ray energy range 10–140 MeV. The Hinotori satellite[3] has been observing the sun in roughly the same energy range. The GAMMA astrophysical module has been used to study solar flares at energies from 30 MeV to 5 GeV (Ref. 4). The detectors of the COMPTON gamma observatory[5,6] span a wider energy range (from 10 keV to 30 GeV).

In this letter we discuss results found on hard radiation in solar flares by the GAMMA-1 telescope, which has, for the first time, detected a prolonged (~ 2 h) γ-ray emission with a high energy (up to several GeV) from a solar flare.[7]

The Soviet–French telescope GAMMA-1 was put in orbit in the summer of 1990. It carried out a program of solar observations in 1991. The composition, operating principle, and working characteristics of the telescope are reported in Refs. 4 and 8. The lowest γ-ray energy which can be detected is 30 MeV. The effective detection area for a source at the axis of the telescope, for an energy $E_\gamma = 100$ MeV, is ~ 180 cm^2.

On the basis of a prediction of a preflare activity, the telescope was oriented toward the sun and was used in a slave mode until the active region of sunspots disappeared at the limb. In this manner, γ-ray fluxes with an energy $E_\gamma \geqslant 30$ MeV from two powerful solar flares, which occurred on 26 March and 15 June of 1991, were detected. Preliminary results and some more accurate later results on the time evolu-

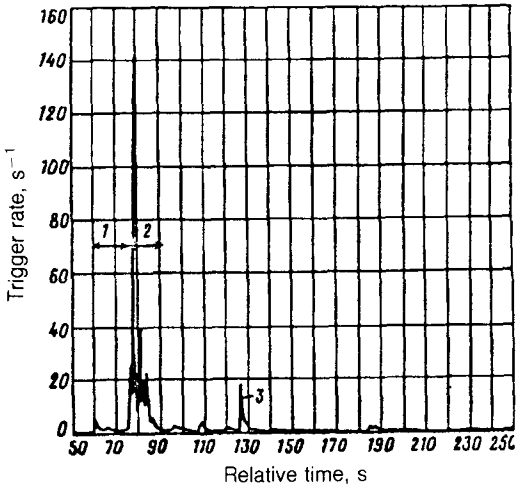

FIG. 1. Time evolution of the solar γ flare on 26.03.91 (the zero on the time scale corresponds to $20^{n}26^{m}41^{s}216$ UT). *1*—Precursor; *2*—main burst; *3*—repeated burst.

tion and energy spectrum of the γ-ray emission in solar flares are reported in Refs. 6 and 9–11. In the present letter we are reporting an analysis of the time evolution of the γ radiation in flares at the highest resolution possible for the telescope, which reveals the temporal structure of flares in greatest detail.

In contrast with a previous analysis of the temporal profile of a flare,[6,11] which was based on the standard time evolution of the telescope count rate over a fixed time interval, we used a method of a "sliding average frequency" in the present study. The frequency at which the γ rays were detected was determined from the time interval between five successive events and was assigned to the last γ ray detected. The dead time of the instrument was taken into account. The time evolution of the sliding average frequency describes the temporal profile of a flare with a high time resolution, despite the smoothing. This resolution is determined by the count rate and is 0.05 s under the best conditions.

The flare of 26 March 1991, of importance 3B/X 4.7, occurred in the central region of the solar disk (28° S, 23° W). In the γ radiation, it lasted about 15 min. The active phase of the γ flare began at $20^{h}27^{m}57^{s}$ UT, which was 2 min after the appearance of optical radiation from the flare, and 8 min after the beginning of the thermal x radiation. According to the customary terminology, these conditions indicate an acceleration of the particles in a second, long stage of the flare.[12]

Figures 1 and 2 show the time evolution of the γ flare of 26 March in various time scales, so that all the details of the temporal structure can be seen. The time t is expressed in seconds with respect to an arbitrary zero, which corresponds to $20^{h}26^{m}41^{s}$, 216 UT. The temporal profile turned out to be more complex than it had appeared to be previously after a standard analysis. On this profile we can clearly see the temporal details which were known previously and also some new features, which had previously been hidden because of the smoothing of the profile during the summation of events over a long time interval. Along with the main pulse of the flare, which lasted 11 s and which consisted of two subpulses with durations of 5 and 6 s,

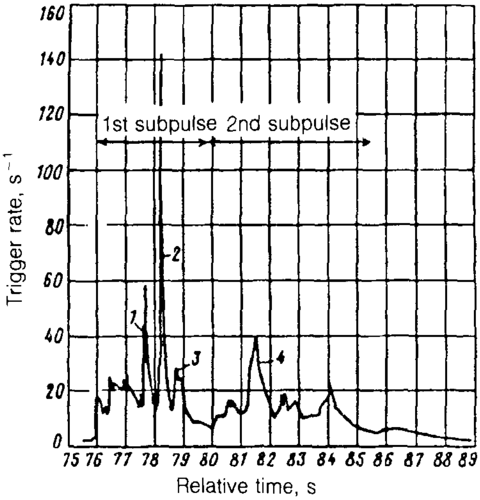

FIG. 2. Time evolution of the main part of the solar γ flare of 26.03.91. *1*—First peak of first subpulse; *2*—second peak of first subpulse; *3*—third peak of first subpulse; *4*—main peak of second subpulse.

repeating bursts of radiation coming at intervals of 10–15 s and 50–60 s, and two additional pulses, which occurred 5 and 8 min after the main pulse (Fig. 1), the temporal profile reveals a fine structure of the subpulses (Fig. 2). The first subpulse is split into three peaks, with maximum frequencies of 60, 140, and 30 Hz and with durations ranging from 0.04 to 0.2 s. The second subpulse consists primarily of a peak at the frequency 40 Hz, whose width is no greater than 0.3 s. The peak flux of γ rays in the energy interval 30–300 MeV reaches 2 $\text{cm}^{-2}\cdot\text{s}^{-1}$ for the narrowest peak, with a duration of about 40 ms and a frequency of 140 Hz. A total of 106 γ rays were detected in the main pulse, in comparison with an expected background of 1.1 events, determined before the flare.

The main pulse of the γ flare is preceded by a smoother increase in the flux of γ radiation. The initial stage of the flare can be seen in Fig. 1. The level of the preflare background for the telescope is 0.1 Hz; it should not have varied by more than 5% (in accordance with the latitudinal variation). However, about 15 s before the main phase of the flare, we observe an increase in the count rate to 1 Hz. It is possible that this precursor, like the main flare, has a temporal structure, but the statistical reliability here is insufficient to support the assertion that this structure exists.

The solar flare on 15 June 1991, of important 3B/X 12+, turned out to be more intense in the x radiation. It occurred near the limb (33° N, 70° W). The GAMMA-1 telescope was able to detect it only 17 min after the optical beginning; the active phase of the flare was lost because of shadowing by the earth. A decaying flux of γ radiation was detected for 37 min, until the satellite passed into the earth's shadow. This flux continued to be visible on the next turn, after the satellite emerged from the shadow, so the total duration of the γ emission was at least 2 h.

Figure 3 shows the time evolution of the γ radiation in the flare of 15 June over the first 15 min after the telescope was turned on (the zero of the time scale corresponds to $8^{\text{h}}38^{\text{m}}41^{\text{s}}$, 323 UT). This flare was more intense, not only in the x-ray range but also in the γ range, as is demonstrated by the greater duration and the flux of γ

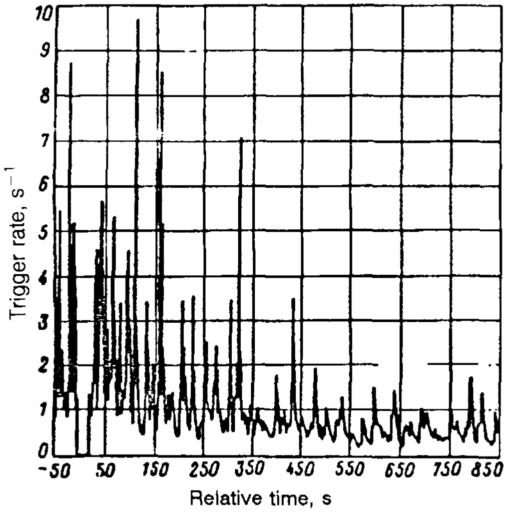

FIG. 3. Time sweep of the solar γ flare of 15.06.91.

rays ($\bar{\nu}=5$–10 Hz in the tail of the flare). The temporal structure is in the form of discrete second-duration pulses which come at intervals of 10–20 s, against a pedestal which varies slowly with the time. However, it must be kept in mind that the statistical reliability of the individual pulses is much lower than for the flare of 26 March; some of the pulses may be random. The low statistical base of γ rays for the individual pulses also rules out an analysis of these pulses to detect a fine structure. In the time evolution there are no significant repeated pulses like those seen in the flare of 26 March. This result is not surprising, since the remote tail of the flare was detected.

An estimate of the reliability of the structural features found in the time evolution of these γ flares was made from the average count rate of the telescope in the peaks. The calculated Poisson probabilities for the random occurrence of the peaks are 4.5×10^{-2}, 2.1×10^{-4}, 3.3×10^{-1} and 1.3×10^{-2} for the first and second subpulses of the flare of 26 March and no more than 5×10^{-3} for the peaks with an amplitude $\nu\geqslant 9$ Hz in the flare of 15 June. Some of the peaks may therefore be random.

In summary, this analysis of the time evolution of the γ emission in an intense solar flare has shown that during the active stage of the flare the emission consists of discrete bursts with an average duration of 10 s, which repeat at intervals from 10 s to several minutes. Each burst, in turn, consists of a series of emission peaks 0.1–0.3 s wide, which come at intervals of a few seconds. This detailed picture of the time evolution of the hard γ radiation is even better than what is currently known about the x radiation and soft γ radiation in solar flares, in which the role of "elementary flare burst" is played by pulses $\simeq 10$ s long which come at intervals of 3–30 s (Ref. 13). We believe that this structure corresponds to discrete γ bursts (subpulses and repeated pulses). If they are assumed to be particle-acceleration events, then the peaks of the fine structure can be associated with a bunching of accelerated beams or with discrete strikes of the target by these beams.

The results found here do not contradict the mechanism of a collective acceleration of protons in a solar flare,[14,15] in which the time scale for acceleration to energies of a few GeV is 10^{-2}–10^{-1} s.

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