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SOLAR FLARES WITH SUSTAINED GAMMA-RAY EMISSION AND SOME CHARACTERISTICS OF HIGH-ENERGY PROTON FLUXES

V.M. Tomozov
Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, tom@iszf.irk.ru

†G.S. Minasyants
Fesenkov Astrophysical Institute, Almaty, Kazakhstan

T.M. Minasyants
Fesenkov Astrophysical Institute, Almaty, Kazakhstan

Abstract. We describe the characteristics of long-term gamma fluxes with quantum energies >100 MeV, obtained from Fermi/LAT data during the impulsive phase of the most energetic flare phenomena. We compare GOES data on proton fluxes with energies >500 MeV with Fermi/LAT data on gamma fluxes for the period 2010–2018. The results of the analysis of all data obtained on 32 gamma-ray flares from the Fermi/LAT catalog show that the flare phenomena can be classified into three different types: type 1 — gamma fluxes accompanied by energetic proton fluxes; type 2 — gamma rays recorded in the absence of increases in proton fluxes; type 3 — gamma fluxes not recorded during observed increases in energetic proton fluxes. The burst character of energy release in the hard X-ray range was noted in some flares.

Keywords: flares, coronal mass ejections, particle acceleration.

INTRODUCTION

The main cause of particle acceleration and heating in the impulsive phase of solar flares is the release of free magnetic energy owing to dissipation in current sheets during magnetic reconnection with the subsequent stochastic acceleration due to the development of plasma instabilities [Altyntsev et al., 1982; Priest, Forbes, 2005; Somov, 2013]. In flares (especially in proton events), particles are also accelerated on shock wave fronts that occur during coronal mass ejections (CMEs) from active regions. According to modern concepts, the occurrence of flares and their associated plasma emissions is related to the imbalance of the magnetic structures of active regions during their evolution. The magnetic field structure of the active region, where filaments are located above polarity inversion lines, is complicated by shear (and other) motions at the footpoints of magnetic loops along magnetic field neutral lines. As a result, a filament (prominence) above the neutral line loses its stability and begins to rise up with acceleration, opening the magnetic structure and forming a CME "core" in the corona [Golovko et al., 1986].

During the impulsive phase in the region of flare energy release there are rapidly moving streams of heated plasma and accelerated charged particles, partially penetrating into the lower layers of the solar atmosphere through magnetic flux tubes. When energetic particles interact with dense plasma, hard X-rays and possibly gamma-radiation are generated at the footpoints of magnetic loops and the plasma is heated. The rapid heating of plasma in the photosphere and chromosphere leads to its "evaporation" and rise, and to filling the entire volume of magnetic arches. During this phase, an increase in the X-ray flux is observed. Then the flare main phase follows when the heated plasma in the arch system radiates in the X-ray spectrum for a long time, gradually losing its energy [Livshits, 2008]. At the same time, particle fluxes accelerated in the flare region interact with developing CME. This causes flare protons to accelerate on the CME shock wave front, which propagates into the upper layers of the corona and into the interplanetary medium. Additional acceleration of particles in the current sheet is also possible in the region behind the CME front going into the corona [Manchester et al., 2017].

According to the results obtained by Murphy et al. [1987], when interacting with the plasma of the solar atmosphere, protons with E>300 MeV can produce neutral and charged pions whose decays generate gamma radiation. When flare protons accelerate to E>500 MeV, neutral pions become sources of emission of gamma-ray quanta with high energies exceeding 100 MeV, detected by Fermi/LAT devices. CME shock waves are considered as the main sources of acceleration of solar protons to E>500 MeV in both the solar corona and the interplanetary medium [Tylka et al., 2014]. Gopalswamy et al. [2018, 2019] have found a linear correlation between the duration of type II radio bursts in the interplanetary medium and that of the sustained gamma-ray emission. This result highlights the important role of CME shock waves in accelerating protons to high energies over long distances in the corona and heliosphere. Share et al. [2017, 2018] have presented and analyzed extensive observational material on 32 flares with the sustained gamma-ray emission recorded by Fermi/LAT in 2008–2017.

In this paper, we compare the intensity of gamma-ray fluxes with E>100 MeV, formed in nuclear reactions of energetic protons (E>500 MeV) during the evolution of flares, with the time of the beginning of

CME; quantitative estimates of the high-energy proton fluxes were obtained from SC instruments. To analyze the events, we use data from the catalog published in [Share et al., 2017, 2018]. We present characteristics of some flare events from the catalog.

ENERGETIC PROTON FLUXES IN FLARES WITH SUSTAINED GAMMA-RAY EMISSION

On October 11, 2013, an active region was located at the heliolatitude E101, i.e. behind the eastern limb, so it was impossible to plot the time profile of the variation in the relative intensity of photospheric bright emission during the flare. Figure 1 illustrates variations in the X-ray flux in the range 1–8 Å for the October 11, 2013 event and its time derivative (GOES data), whose zero value defines the boundary between the flare impulsive and main phases. As previously shown in [Minasyants et al., 2018], the profile of the X-ray flux derivative during the impulsive phase correlates well with the behavior of the relative intensity of the flare plasma particle flux at the photospheric level λ1700 Å. Due to the relatively long interval of interaction between CME and the plasma particle flux of the flare in the October 11, 2013 event, it was possible to observe in more detail the variations in the F_γ gamma-ray emission flux with E>100 MeV.

The energy release in solar flares is often irregular and is recorded in the form of bursts, as confirmed by laboratory experiments [Altyntsev et al., 1982; Priest, Forbes, 2005]. A similar pattern of energy release was observed in the hard X-ray spectrum in the September 10, 2017 event (see Figure 1, *b*). Minasyants et al. [2019] for the September 10, 2017 event have compared the time variations in the characteristics of fluxes of gamma-ray quantum with E>100 MeV and protons. The observed similarity in the behavior of these parameters confirmed the main role of protons in forming the high-energy gamma-ray emission during the flare impulsive phase. The very high velocity during propagation of the CME shock front on September 10, 2017 undoubtedly affected the gamma-ray flux parameters since there was an increase in F_γ with E>100 MeV by almost two orders of magnitude compared to other events (Table, column 6): F_γ=0.013 cm^{-2} s^{-1}. The gamma flux turned out to be maximum for gamma-ray events over the entire period of Fermi/LAT observations of the Sun.

We compare the times of the beginning of CME, the increase in gamma-ray quantum fluxes with E>100 MeV, and flare maximum from variations in the relative intensity of photospheric emission during the flare impulsive phase. To do this, we analyze Fermi data on gamma-ray emission, reported in [Share et al., 2017, 2018; Omodei et al., 2018]. The August 9, 2011 event is interesting because the appearance of CME (at 08:02 UT) coincided with the maximum of the flare impulsive phase, which caused particle acceleration and plasma heating. As a result, in this event, the acceleration of particles owing to magnetic reconnection and the additional acceleration of protons on the CME shock front (typical process for the main phase in long-term proton events) coincide in time with the flare impulsive phase.

Observations of gamma fluxes with E>100 MeV accompanying solar flares at time intervals from minutes to hours have shown that high-energy particles interacting with the solar atmosphere can accumulate and/or accelerate for a relatively long time. The cases when the gamma-ray emission was recorded even with the appearance of CME behind the solar limb, as observed from Earth, provided favorable conditions for studying the role of CME-driven coronal shock waves. Evidence has been obtained that high-energy protons generating the sustained gamma-ray emission owe their origin to CME-driven shock waves, just as solar energetic particles measured in the interplanetary medium [Plotnikov et al., 2017; Grechnev et al., 2018].

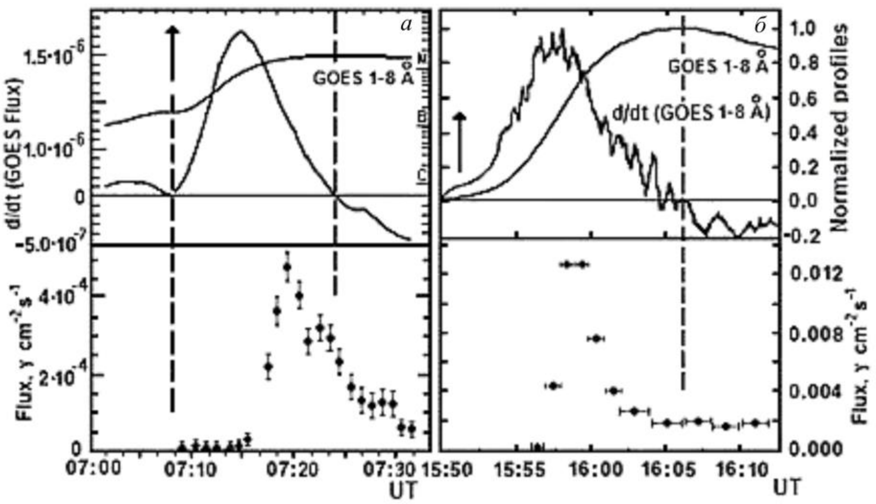

Figure 1. An X-ray flux F_X in the range 1–8 Å and its time derivative *d/dt* (at the top, right panel — normalized curves), as well as a gamma flux with E>100 MeV (at the bottom) [Minasyants et al., 2019] for the events M1.9 (N21, E101) on October 11, 2013 (*a*) and X8.2 (S08, W88) on September 10, 2017 (*b*). The flare impulsive phase: 07:08–07:24 UT (*a*) and 15:50–16:06 UT (*b*); the CME onset (shown by the vertical arrow): 07:08 UT (*a*) and 15:51 UT (*b*); vertical dashed lines denote the flare impulsive phase. The data has been taken from the catalog of solar flares [https://cdaw.gsfc.nasa.gov/C M E_list/UNI V ERSAL_ver1/2017_09/univ2017_09.html]

Event characteristics as observed by different spacecraft

No.	Flare dates and onset time (UT)	Flare X-ray class and coordinates	CME velocity, km/s	Proton flux with E>10 MeV, pfu	Duration of gamma fluxes with E>100 MeV, hr	$F_{\gamma\,max}$ with E>100 MeV, $cm^{-2}\cdot s^{-1}$
	1	2	3	4	5	6
1	Jan. 27, 2012, 17:37	X1.7 N35W81	2508	796	2.0	$3.5\cdot10^{-5}$
2	Mar. 07, 2012, 00:02	X5.4 N17E15	2684	6530	14.4	$2.0\cdot10^{-3}$
3	May 17, 2012, 01:25	M5.1 N05W77	1582	255	2.1	$1.2\cdot10^{-5}$
4	Sep. 10, 2017, 15:44	X8.2 S08W83	3163	1490	11.6	$1.3\cdot10^{-2}$
5	Sep. 06, 2011, 22:12	X2.1 N14W18	1000	8	0.2	$1.7\cdot10^{-4}$
6	Sep. 07, 2011, 22:32	X1.8 N18W32	792	–	0.3	$8.0\cdot10^{-6}$
7	Jan. 23, 2012, 03:38	M8.7 N33W21	2175	6310	5.3	$2.0\cdot10^{-5}$
8	Sep. 06, 2017, 11:53	X9.3 S08W33	1571	15	9.7	$4.5\cdot10^{-5}$
9	May 22, 2013, 13:08	M5.0 N15W70	1466	1660	–	–

In most cases, the CME onset preceded the beginning of the flare impulsive phase. In total, in three events — March 7, 2012, February 25, 2014, and September 6, 2011 — gamma fluxes with E>100 MeV were recorded during the flare main phase within the values related to the impulsive phase of these flares.

We have analyzed GOES/HEPAD observational data on proton fluxes with different energies recorded near Earth in 2010–2018. Proton fluxes with energies of 375, 465, 605 MeV, and <700 MeV were detected only in five of eight flare events (see Table, events 1–4, 9). Note that only four events (No. 1–4: January 27, March 7, May 17, 2012, and September 10, 2017) were related to the long-term gamma-ray flares with E>100 MeV. The May 22, 2013 flare was not linked to these events as it caused only a short-term increase in the gamma flux, which only slightly exceeded the background level (Figures 2, 3). For the events having a gamma-ray emission with E<100 MeV, the proton fluxes with E>500 MeV recorded by the GOES spacecraft near Earth corresponded to the conditions of effective interaction of protons with the surrounding plasma during the formation of gamma-ray quanta. Share et al. [2017] have found that large-scale solar energetic proton fluxes near Earth are subject to minimum particle losses when solar flares occur near the nominal longitude W58. These losses increase exponentially in both directions in the longitude interval between W20 and W90, and beyond this interval the results of extrapolation of particle fluxes may be subject to errors.

Table provides information about individual flares and characteristics of their attendant phenomena. Column 3 shows CME linear velocities; column 4, proton fluxes with E>10 MeV (according to additional data, 8 pfu and 15 pfu proton fluxes were recorded in the September 6, 2011 and September 6, 2017 flares respectively); column 5 lists durations (in hours) of gamma fluxes with E>100 MeV; column 6 presents maximum values

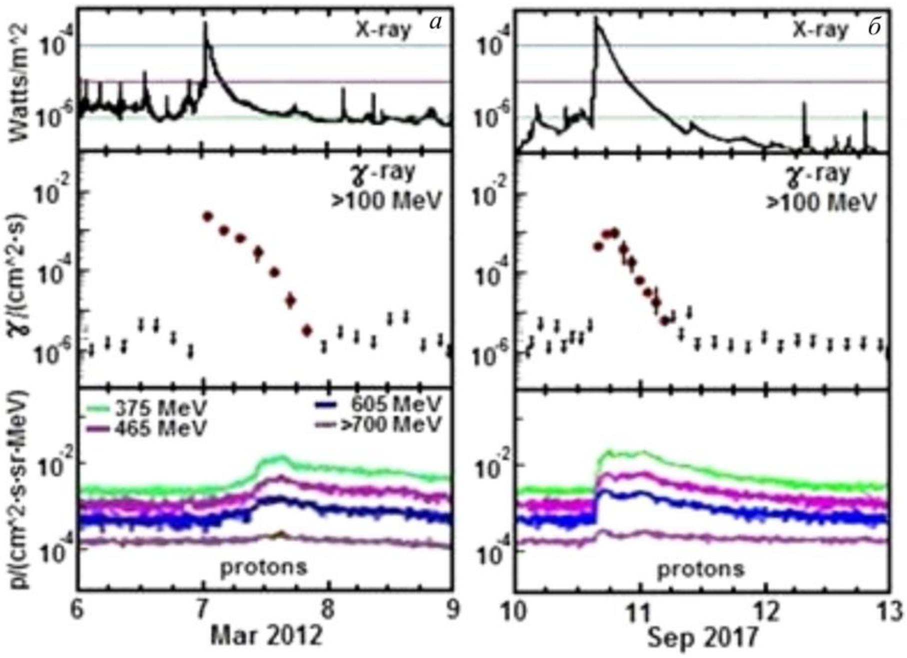

Figure 2. Evolution of X-ray fluxes in the range 1–8 Å (GOES), gamma fluxes with E>100 MeV (Fermi/LAT), and high-energy proton fluxes (GOES) for class 1 events: March 7, 2012 (*a*) ; September 10, 2017 (*b*). GOES data [https://www.ngdc.noaa.gov/stp/sa tellite/goes/dataaccess.html]

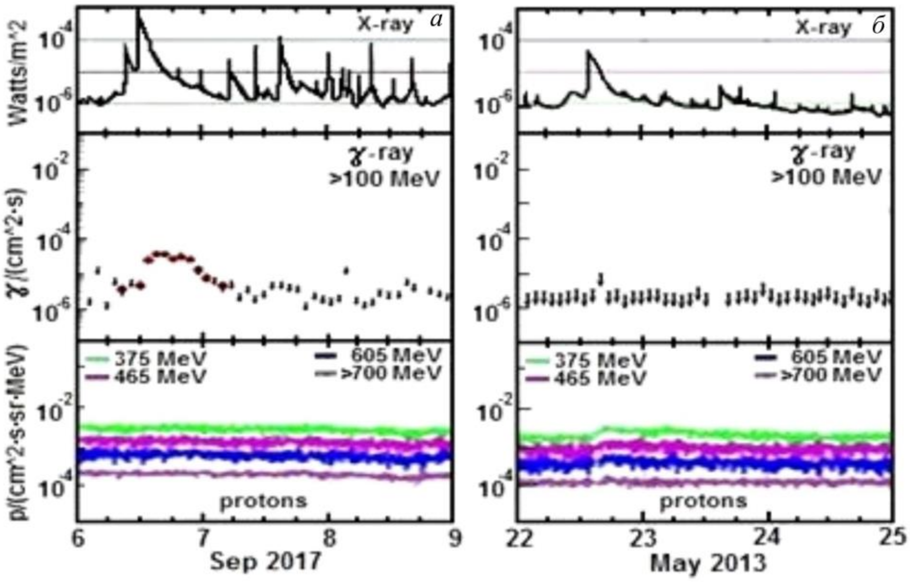

Figure 3. Evolution of X-ray fluxes in the range 1–8 Å (GOES), gamma fluxes with energies >100 MeV (Fermi/LAT), and high-energy proton fluxes (GOES) for events of classes 2 (September 6, 2017 (*a*)) and 3 (May 22, 2013 (*b*)). GOES data [https://www.ngdc.noaa.gov/stp/satellite/goes/dataaccess.html]

of gamma fluxes $F_{\gamma\ max}$ with E<100 MeV (except for the May 22, 2013 event). When plotting gamma fluxes with E>100 MeV, we used Fermi/LAT data and processed them by the MLP (maxim-likely plots) method [Share et al., 2018]. We employed SOHO/LASCO observational data to examine the CME structure and other characteristics.

By comparing proton fluxes with E>500 MeV and gamma fluxes with E>100 MeV from flares, we have identified events of three different types: type 1 — gamma-ray events accompanied by high-energy proton fluxes near Earth (events No. 1–4 in Table); type 2 — events with gamma-ray emission with E>100 MeV, but without enhanced fluxes of high-energy protons (events No. 5–8); type 3 — events characterized by an increase in proton fluxes of sufficiently high energies in the absence of gamma-ray emission (event No. 9; similar events are apparently unrelated to gamma-ray flares).

Event No. 9 occurred on May 22, 2013: an M5 X-ray flare (began at 13:08 UT, N15 W70) included a halo-type CME with V=1466 km/s and a 1660 pfu proton flux with E>10 MeV. A slight increase in the flux of high-energy protons, including energies > 700 MeV, was recorded in this flare, but Fermi/LAT did not detect the gamma-ray emission with E>100 MeV. The flare began at 13:08 UT; and CME, at 12:25 UT, i.e. CME occurred somewhat later than the flare impulsive phase. Consequently, high-energy protons accelerated at a greater distance from the flare region at a relatively low coronal density.

The March 7, 2012 flare (see Figure 2) features a significant time delay in the appearance of maximum high-energy proton fluxes relative to the maximum emission of the flare in the X-ray spectrum. This was likely to be due to the position of the flare centroid in longitude (N17E15).

Each solar flare accompanied by gamma-ray emission is unique. For example, the September 6, 2011 event (X2.1, N14W18) was characterized only by a weak increase in proton fluxes with E>10 MeV (8 pfu) and hence by an almost complete absence of high-energy proton fluxes in near-Earth observations. The same picture was observed in the September 7, 2011 event (X2.1, N18W32) with similar characteristics of proton fluxes. The September 6 flare belonged to sources of gamma-ray emission with E>100 MeV and $F_{\gamma\ max}$, which was the sixth most intense among those recorded, and in the September 7, 2011 event the observed maximum gamma flux was 35 times lower. In the January 23, 2012 event, there was a gamma flux with E>100 MeV and an increase in proton fluxes with energies of 375 and 465 MeV, but no increase in the proton flux with E>500 MeV was detected.

SUMMARY AND CONCLUSIONS

By analyzing the existing views about energy release in solar flares with CMEs and sustained gamma-ray emission, we have confirmed that the occurrence of a coronal mass ejection is closely related in time to the flare impulsive phase [Minasyants et al., 2019]. It is known that the most effective acceleration of particles on CME shock wave fronts is observed when CME occurs and develops both before and at the maximum of the flare impulsive phase, followed by high-energy gamma fluxes with E>100 MeV. Among the events considered, only in the September 6, 2011 flare F_γ with E>100 MeV in the main phase slightly exceeded F_γ in the impulsive phase. In other cases, maximum gamma fluxes were recorded during the flare impulsive phase (see Figure 1). Consequently, the development of CME-driven shock waves, which is considered as the dominant process of proton acceleration in the main phase of long-term gamma-ray flares, in some cases occurs during the impulsive phase. In addition, almost all of the above figures clearly show that in the hard X-ray range energy is released in the form of individual bursts (there is evidence of similar behavior in the gamma-ray emission too). It is known that energy release in current sheets of solar flares is also irregular and is subject to fluctuations. This fact was confirmed during laboratory experiments with current sheets [Altyntsev et al., 1982]. Comparison of proton fluxes with E>500 MeV and gamma fluxes with E>100 MeV from flares has shown that the events considered can be classified into three types: type 1 — gamma fluxes accompanied by energetic proton fluxes; type 2 — gamma-ray emission recorded in the absence of increases in proton fluxes; type 3 — no gamma quantum fluxes recorded during the observed increases in energetic proton fluxes. The absence of increases in proton fluxes in long-term type 2 flares is presumably due to conditions of their propagation in the interplanetary medium, and type 3 events may not be related to flares with sustained gamma-ray emission at all (for example, the May 22, 2013 flare).

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