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COMPARISON OF CHARACTERISTICS OF PHOTONS FLUXES VARIOUS ENERGIES IN THE DEVELOPMENT OF SOLAR GAMMA FLARES

Abstract. The characteristics of photons fluxes of various energies during the development of flares with high-energy gamma rays are considered. Observations on FERMI, SDO, GOES spacecraft were used. Photons fluxes with energies $E_k = (12\text{-}25)$ keV, $E_k = (50\text{-}100)$ keV and $E_k > 100$ MeV for 19 flares events were compared. Comparison of quantitative and temporal characteristics of photons profiles of X-ray energy range with properties of bright flares plasma showed that for almost all events the moments of onset of peaks (12-25) keV and maximum values (50-100) keV of photons in counts/s refer to the time interval from the beginning of flares development within 22 minutes. The same result is noted for events with the most intense maximum fluxes in ($\gamma \cdot cm^{-2} \cdot s^{-1}$) for high energy photons > 100 MeV. This supports the assumption of the most effective acceleration of particles during the simultaneous development of the direct flare process and the accompanying coronal mass injection, resulting in the creation of maximum fluxes values of highly energetic gamma photons. Flares events with the most intense maximum fluxes in ($\gamma \cdot cm^{-2} \cdot s^{-1}$) for high energy photons > 100 MeV do not show the highest values of the number of photons in the X-ray energy ranges, indicating differences in the efficiency of photons formation mechanisms of different energies. According to observations, the most likely source of quantitative amplification of flares photons with energies (12-25) keV is the results of bremsstrahlung radiation of bright flares emission in corona, and for photons with energies (50-100) keV - in the area of upper photosphere and temperature minimum.

Keywords: Solar flares, flare plasma emission, coronal mass ejection, X-ray and gamma ray.

Introduction. With use of the observation data obtained by means of the modern solar spacecrafts (SC) there was an opportunity to study properties of flare fluxes photons of different energy. During the impulse phase of flares, the main mechanism of particle acceleration is the release of free magnetic energy in the active region due to its dissipation in current sheets caused by magnetic reconnection followed by stochastic acceleration during the development of various plasma instabilities [1-3]. The process of magnetic reconnection occurs in both the corona and the chromosphere of the Sun [4]. As a result of the effect of magnetic reconnection, flows of fast-moving plasma, heat waves and highly energetic charged particles are observed from the area of primary energy release, some of which propagate along magnetic flux tubes into the underlying layers of the solar atmosphere. When interacting with denser plasma in loop bases, X-rays, gamma rays are generated and plasma is heated. Rapid heating of the plasma in the photosphere and chromosphere results in its "evaporation" and rising upward and filling the entire volume of magnetic arches. During this period, the greatest increase in soft X-rays is observed.

It is generally assumed that the occurrence of flares and associated coronal mass ejections (CME) is closely related to the imbalance of magnetic structures of the active regions during their evolution. As the magnetic structures of the active regions with the magnetic field polarities on the line of separation develop, the filaments are continuously complicated. Above the filaments there are closed loops of magnetic field, which create a generally closed magnetic configuration of the entire active area up to coronal heights. At continuous action of shear movements on the bases of magnetic loops along the line of polarity separation, the filament (prominence) loses stability and begins to climb up rapidly, opening the magnetic structure and forming the "core" of CME. It is possible that it is with the process of "breaking" the vertices of coronal magnetic loops that the moving filament is associated with the impulse phase of the flare, because energy release is recorded in these areas and hard X-ray sources are observed.

An important source of particle acceleration in flares is their acceleration on shock wave fronts arising from the propagation of CME from the active regions to the upper layers of the corona and in the interplanetary environment. When protons of flares accelerate to $E_k > 500$ MeV energies, due to their nuclear interaction with the substance of the solar atmosphere, neutral pion are generated [5], at the decay of which gamma rays of high energy photons > 100 MeV produces.

The given physical, structural and dynamic properties of the active regions during the development of flares processes indicate the possible action of several mechanisms in the formation of photons of different energies.

Results of observation data processing. Properties fluxes of flares photons with energies E_k = (12-25) keV, E_k = (50-100) keV and $E_k > 100$ MeV were compared. From the list of 32 events presented in the works G.H. Share et al. [6,7] and with time resolution of 1 min for gamma ray fluxes $E_k > 100$ MeV, the only 19 of events that occurred in the period 2011-2017 were selected. This limitation is due to the mandatory presence in the observation data of profiles of quantitative changes of photons with energies E_k = (12-25) keV, E_k = (50-100) keV. Observations from FERMI spacecraft using GBM and LAT instruments were used.

Table 1 shows some characteristics of photon fluxes in X-ray energy intervals (12-25) keV and (50-100) keV, as well as of sustained gamma ray with energies > 100 MeV.

Table 1 - Characteristics of flares and fluxes of photons different energies

	Date GOES X-ray Class, Start	GBM peak (12-25) keV counts/s UT	GBM max (50-100) keV counts/s UT	LAT $F^{max}_{\gamma>100MeV}$ $\gamma \cdot cm^{-2} \cdot s^{-1}$ UT
1	07/03/2011 M3.7 19:43	$1.2 \cdot 10^5$ 20:03	$1.0 \cdot 10^4$ 20:02	$2.3 \cdot 10^{-5}$ 20:26
2	07/06/2011 M2.5 06:16	$6.9 \cdot 10^4$ 06:26	$1.3 \cdot 10^4$ 06:25	$5.5 \cdot 10^{-5}$ 08:00
3	04/08/2011 M9.3 03:41	$5.9 \cdot 10^5$ 03:54	$1.5 \cdot 10^4$ 03:52	$4.3 \cdot 10^{-5}$ 05:06
4	09/08/2011 X6.9 07:48	$1.2 \cdot 10^6$ 08:08	$7.0 \cdot 10^5$ 08:06	$7.7 \cdot 10^{-4}$ 08:03
5	06/09/2011 X2.1 22:12	$8.7 \cdot 10^5$ 22:20	$4.2 \cdot 10^5$ 22:19	$5.7 \cdot 10^{-4}$ 22:27
6	07/09/2011 X1.8 22:32	$1.0 \cdot 10^6$ 22:38	$1.7 \cdot 10^5$ 22:37	$1.6 \cdot 10^{-5}$ 23:37
7	24/09/2011 X1.9 09:21	$8.0 \cdot 10^5$ 09:42	$4.0 \cdot 10^5$ 09:35	$1.6 \cdot 10^{-4}$ 09:43
8	09/03/2012 M6.3 03:22	$1.3 \cdot 10^6$ 03:39	$8.0 \cdot 10^3$ 03:41	$1.3 \cdot 10^{-5}$ 03:50
9	03/06/2012 M3.3 17:48	$1.7 \cdot 10^5$ 17:55	$2.5 \cdot 10^4$ 17:53	$3.8 \cdot 10^{-4}$ 17:54
10	23/10/2012 X1.8 03:13	$8.3 \cdot 10^5$ 03:16	$2.5 \cdot 10^5$ 03:15	$2.3 \cdot 10^{-5}$ 04:17
11	27/11/2012 M1.6 15:52	$1.1 \cdot 10^5$ 15:57	$9.0 \cdot 10^3$ 15:55	$2.5 \cdot 10^{-5}$ 15:59
12	11/04/2013 M6.5 06:55	$2.1 \cdot 10^5$ 07:10	$3.0 \cdot 10^3$ 07:10	$1.7 \cdot 10^{-4}$ 07:13
13	13/05/2013 X2.8 15:48	$7.8 \cdot 10^5$ 16:07	$2.3 \cdot 10^5$ 16:04	$3.8 \cdot 10^{-5}$ 17:42
14	14/05/2013 X3.2 01:00	$9.4 \cdot 10^5$ 01:13	$2.4 \cdot 10^5$ 01:08	$1.7 \cdot 10^{-5}$ 01:42
15	11/10/2013 M4.9 07:01	$4.1 \cdot 10^4$ 07:17	$2.2 \cdot 10^2$ 07:10	$4.7 \cdot 10^{-4}$ 07:19
16	25/10/2013 X1.7 07:53	$2.7 \cdot 10^5$ 08:07	$2.6 \cdot 10^3$ 08:07	$2.5 \cdot 10^{-5}$ 08:17
17	28/10/2013 M4.4 14:57	$1.6 \cdot 10^5$ 14:59	$6.0 \cdot 10^2$ 14:59	$2.6 \cdot 10^{-5}$ 15:45
18	25/02/2014 X4.9 00:39	$8.1 \cdot 10^5$ 00:53	$5.0 \cdot 10^5$ 00:46	$1.5 \cdot 10^{-3}$ 01:22
19	10/09/2017 X8.2 15:44	$1.0 \cdot 10^6$ 16:22	$8.0 \cdot 10^5$ 16:12	$1.3 \cdot 10^{-2}$ 16:00

The second column of the table shows the peak values of the number of photons (12-25) keV counts/s determined for each event during the maximum period of their fluxes and presented on the site of FERMI GBM. Using FERMI GBM QUICKLOOK graphs, the maximum photons (50-100) keV counts/s (third column) were determined. And accordingly, to obtain maximum photons fluxes F^{max} $\gamma \cdot cm^{-2} \cdot s^{-1}$ with energies > 100 MeV and time resolution 1 minute (fourth column), were used observation graphs on the

FERMI LAT and published in [6,7]. In table additionally indicates the start time of each flares event, as well as the moments of onset of peaks and maximum quantitative values for photons of different energies.

Using the data presented in the table, separate graphs were constructed taking into account the photon energy intervals showing the peak and maximum photons fluxes values for the respective moment after the flare began. All considered events are conditionally divided into two groups: the first (red dots) - flares, which had the highest values of gamma-ray fluxes $F^{max}_{\gamma>100MeV}>1.0\cdot10^{-4}$ ($\gamma\cdot cm^{-2}\cdot s^{-1}$) and the second group (black dots) - the rest, with smaller values.

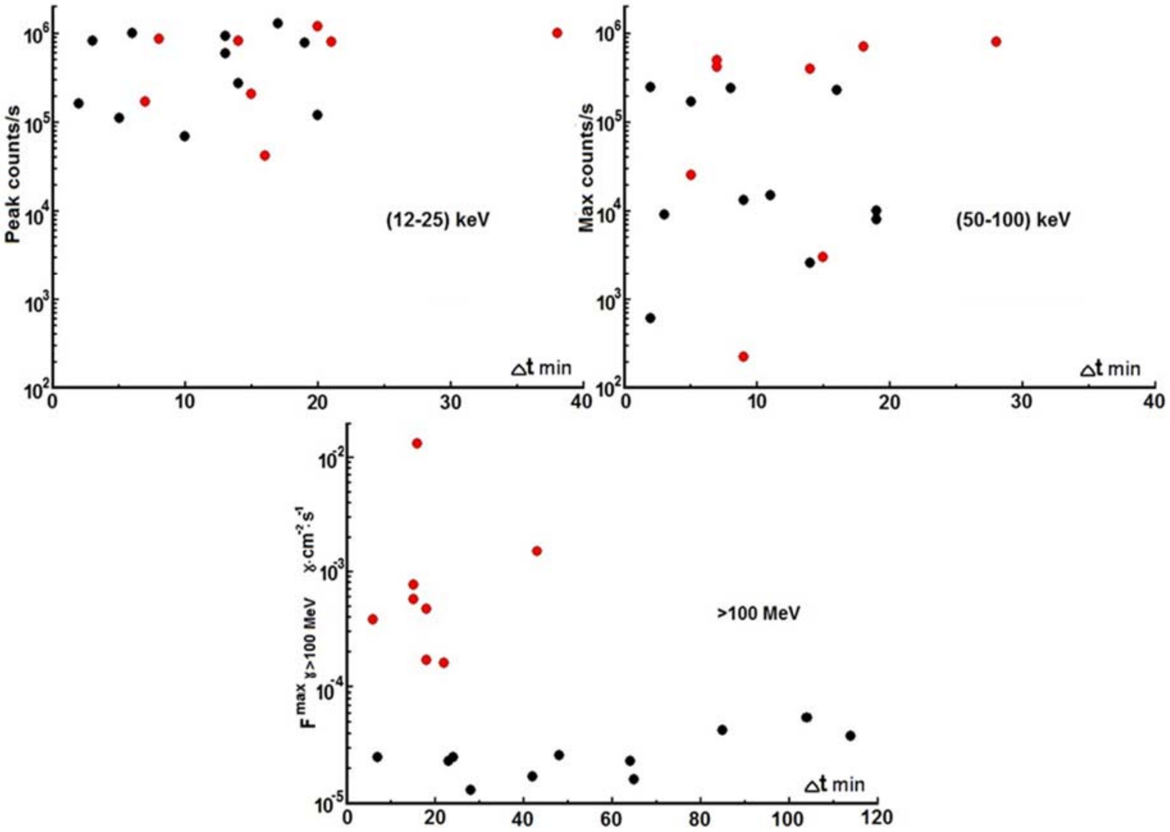

Figure 1 - Comparison of peak values (peak counts·s^{-1}) of photons (12-25) keV, maximum values (max counts · s-1) of photons (50-100) keV and maximum values of gamma-fluxes ($F^{max}_{\gamma>100MeV}$ $\gamma\cdot cm^{-2}\cdot s^{-1}$) with time interval value in minutes after flares start

Both upper graphs in figure 1 with quantitative values of X-ray energy photons show approximately the same contribution of both groups of events to the range of observed values. This indicates that there is no clear link between the effectiveness of photons amplification mechanisms with X-ray and gamma energies. A clear example: of all the events taken for consideration, the lowest values of the number of photons with X-ray energies were found for the flare of October 11, 2013, included in the 1-st group of events with the highest values fluxes of photons with gamma energy >100 MeV.

Except for one event, for all others, the moments of emergence of peaks (12-25) keV and the maximum values (50-100) keV of photons in counts/s lie in the range of time from the beginning of development of flares within 22 min. The same conditions correspond also to the most intensive maximum fluxes in ($\gamma\cdot cm^{-2}\cdot s^{-1}$) for photons of gamma energy >100 MeV. This supports the conclusion in the article [8] about the most efficient formation of high-energy gamma rays due to the very intense acceleration of particles (with the energy of protons E_k > 500 MeV), when flare development simultaneously with shock waves of CME.

In most events, the peak values for (12-25) keV were observed slightly later than maxima in the profiles of (50-100) keV.

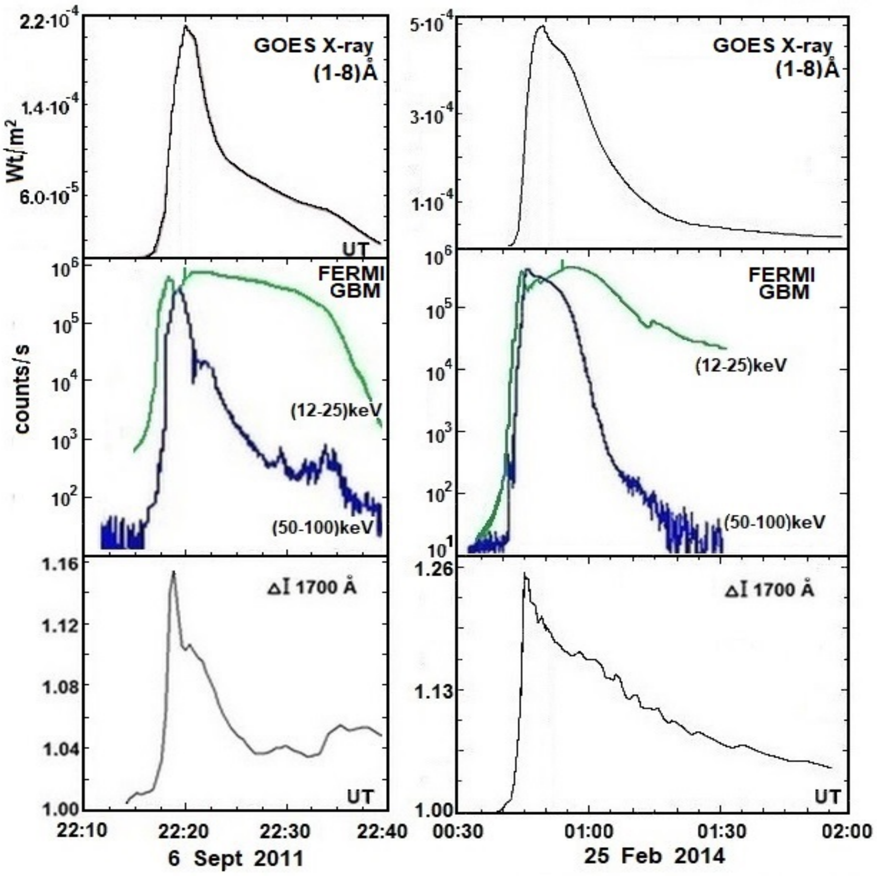

Figure 2 - Comparison of the temporary development profiles of GOES X-ray (1-8) Ǻ flares, quantitative changes of photons (12-25) keV, (50-100) keV and relative ultraviolet intensity of flares emission for the events of September 6, 2011 and February 25, 2014. Peaks photons (12-25) keV marked on the corresponding profiles with small vertical ledges

Comparison of profiles of temporary changes of quantity of photons to energy (50-100) keV shows their good coincidence to relative of photosphere of flare emission ΔI λ1700 Ǻ. This is expressed not only in the similarity of profiles view, but also, most importantly, in the simultaneous onset of maximum values. The corresponding photons profiles with energies (12-25) keV show a longer time interval with maximum values, which is most characteristic of changes in the intensity of flares emission in the corona.

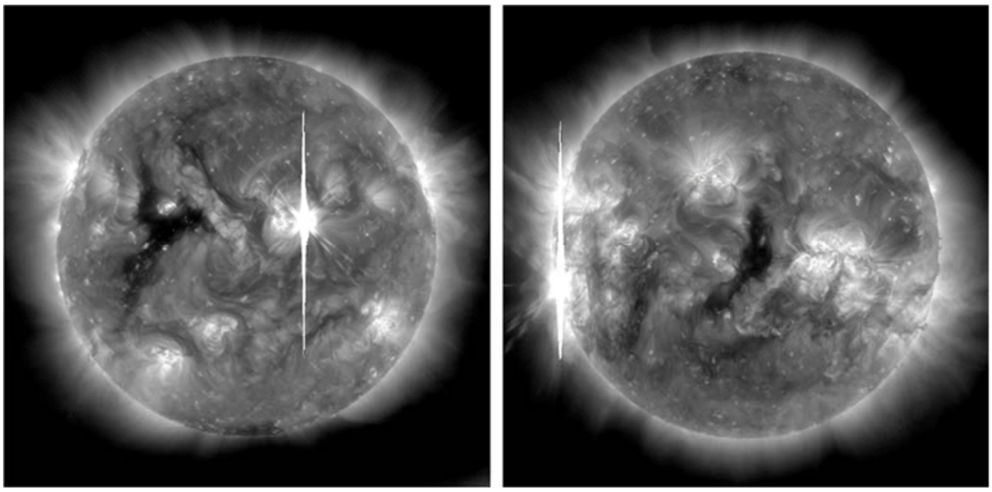

Figure 3 - Fe λ193Å corona photogeliograms (data spacecraft SDO) 6 September 2011 22:20:19 and 25 February 2014 00:53:30

By way of example, Figure 3 shows images of the λ193Å corona (Fe XII, XXIV) obtained on the SDO for the events of September 6, 2011 and February 25, 2014 during peaks quantity of photons (12-25) keV. Bright rays from region of flares plasma directed in opposite directions indicate the presence of solar excess intensity at these moments for the spacecraft photo matrix pixels in imaging.

This results in an observed overflowing of charges to adjacent pixels having no excess of them - the instrumental effect of blooming. Coronal photogeliograms most accurately reflect changes in both luminance and time characteristics of photons having energy (12-25) keV.

Thus, it is possible to assume the source of excess number of photons with energies (12-25) keV - bremsstrahlung radiation due to of flare emission coronal plasma (λ193Å), and for photons (50-100) keV due to bright emission of photospheric plasma (λ1700Å).

Main results and conclusion. The processing of observation material obtained on modern spacecrafts allows to detect new properties in the development of traditionally studied phenomena of solar activity.

It has been found that the maximum values of the quantitative characteristics of photon flares fluxes having X-ray energy at intervals (12-25) keV and (50-100) keV are observed during the initial development period of the flares, within 22 minutes. But the most surprising thing is that such a picture is present for the most powerful $F^{max}_{\gamma>100MeV}>1.0\cdot10^{-4}$ ($\gamma\cdot cm^{-2}\cdot s^{-1}$) fluxes of photons gamma rays. This indicates the most effective particle acceleration with the simultaneous development of the flare process and high-speed coronal ejection. This results in the formation of the most powerful fluxes of energetic gamma photons.

The photons fluxes characteristics in the X-ray energy intervals (12-25) keV and (50-100) keV are determined by the behavior of the bright flare emission in the corona (for the first interval) and in the photosphere, respectively, for the second energy interval.

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КҮННІҢ ГАММА-СӘУЛЕЛЕНУІНІҢ ДАМУЫ КЕЗІНДЕ ӘРТҮРЛІ ЭНЕРГИЯЛЫ ФОТОНДАРДЫҢ СӘУЛЕЛЕНУ АҒЫНЫНЫҢ СИПАТТАМАЛАРЫН САЛЫСТЫРУ

Аннотация. Жоғары энергиялы гамма-сәулеленуінің жарқылы кезіндегі әртүрлі энергиялы фотон ағындарының сипаттамалары қарастырылды. Біз FERMI, SDO, GOES ғарыштық аппараттарының бақылау мәліметтерін пайдаландық. 19 жарқыл үшін Ek = (12-25) keV, E_k = (50-100) keV және E_k>100 MeV энергиялы фотон ағындарына салыстырулар жүргізілді. Рентген сәулелерінің энергиялық аймағының фотон профильдерінің сандық және уақытша сипаттамаларын жарқын алау плазмасының қасиеттерімен салыстыру барлық оқиғалар үшін шыңның басталуы (12–25) keV және максималды мәндері (50–100) keV, фотондардың counts/s даму уақыт аралығының 22 минутке созылады. Дәл осындай нәтиже жоғары энергиялы фотондар үшін >100 MeV максималды ағындары бар оқиғаларда байқалады (γ $см^{-2}$ $с^{-1}$). Бұл тікелей алау процесінің бір мезгілде дамуы кезінде бөлшектердің үдеуін және жарылыс кезінде жүретін тәждік массаның шығуын растайды, нәтижесінде жоғары энергиялы гамма-сәулелерінің максималды ағындары пайда болады. Жоғары энергиялы фотондар үшін >100 MeV максималды ағындары (γ $см^{-2}$ $с^{-1}$) бар жарқылдар оқиғалары рентгендік энергия диапазонындағы фотон санының ең жоғары мәндерін көрсетпейді, бұл әртүрлі энергиялы фотондарының түзілу механизмдерінің тиімділігіндегі айырмашылықтарды көрсетеді. Рентген аймағында жарқ етулердің дамуы аяқталған уақыттан кейін гамма сәулелену ағынының макисмалды күшейуі, жоғары энергиялы фотондар үшін >100 MeV барлық төменгі шамадағы оқиғалар үшін бақыланады. Сондықтан да, гамма сәулелер ағынының қарқынды дамуының күшейуінің максималды мәнге жетуі күн тәжінің шығатын ағындары қоздыратын соққы толқындар болуы мүмкін.

Уақыт өте келе фотондар санының кескінінің өзгерулерін (50-100) keV энергиямен салыстыру кезінде, оның ΔI λ1700Ǻ салыстырмалы фотосферадағы жарқылды плазманың интенсивтілігімен жақсы сәйкес келетіндігін көрсетеді. Бұл тек кескіннің түрінің ұқсастығын ғана емес, сонымен бірге максималды мәндердің бір уақытта басталуын көрсетеді. (12–25) кэВ энергиялы фотондарға сәйкес кескіндер максималды мәндермен ұзақ уақыт аралығын көрсетеді, бұл күн тәждегі жарқылды сәулеленуінің интесивтілігінің өзгеруіне тән. Көптеген жағдайларда, (12–25) кэВ шыңы кескіндердегі максимумнан (50-100) кэВ-ге қарағанда біршама кешірек болады. Бақылауларға сәйкес, (12-25) keV энергиялы фотондар жарқылының сандық күшейу көзі, күн тәжінің аймағында жарықырау кезіндегі тежегіш сәулеленуі себеп, ал (50-100) keV энергиялы фотондар үшін фотосфера аймағы және температура минимумы болып табылады.

Түйін сөздер: күн жарқылы, жарық эмиссиялы плазмалар, күн тәжінен шығарылатын массалар, рентген және гамма сәулеленулері.

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СОПОСТАВЛЕНИЕ ХАРАКТЕРИСТИК ПОТОКОВ ИЗЛУЧЕНИЯ ФОТОНОВ РАЗНЫХ ЭНЕРГИЙ ПРИ РАЗВИТИИ СОЛНЕЧНЫХ ГАММА-ВСПЫШЕК

Аннотация. Рассмотрены характеристики потоков фотонов различных энергий при развитии вспышек с высокоэнергичным гамма-излучением. Использовались данные наблюдений на космических аппаратах FERMI, SDO, GOES. Проведено сопоставление потоков фотонов с энергиями E_k = (12-25) keV, E_k = (50-100) keV и E_k>100 MeV для 19 вспышечных событий. Сравнение количественных и временных характеристик профилей фотонов рентгеновского диапазона энергий со свойствами яркой вспышечной плазмы показало, что почти для всех событий моменты наступления пиковых (12-25) keV и максимальных значений (50-100) keV фотонов в counts/s относятся к интервалу времени от начала развития вспышек в пределах 22 минут. Такой же результат отмечается и для событий с наиболее интенсивными максимальными потоками в ($\gamma \cdot cm^{-2} \cdot s^{-1}$) для фотонов высоких энергий >100 MeV. Это подтверждает предположение о наиболее эффективном ускорении частиц в период одновременного развития прямого вспышечного процесса и сопровождающего вспышку коронального выброса массы, приводящим в итоге к возникновению максимальных значений потоков высокоэнергичных гамма-квантов. Вспышечные события с наиболее интенсивными максимальными потоками в ($\gamma \cdot cm^{-2} \cdot s^{-1}$) для фотонов высоких энергий >100 MeV не показывают наиболее высоких значений количества фотонов в диапазонах рентгеновских энергий, что указывает на отличия в эффективности механизмов образования фотонов разных энергий. Практически для всех событий с пониженными значениями количества фотонов высоких энергий >100 MeV наблюдается максимальное усиление потоков гамма излучения в период после окончания развития вспышек в рентгеновском диапазоне. Поэтому в этих случаях определяющую роль в усилении потоков гамма излучения до максимальных значений играют, вероятнее всего, ударные волны, возбуждаемые корональными выбросами.

Сопоставление профилей изменения со временем количества фотонов с энергиями (50-100) keV показывает их хорошее совпадение с относительной интенсивностью фотосферной вспышечной плазмы ΔI λ1700Ǻ. Это выражается не только в подобии вида профилей, но и, что особенно важно, в одновременном наступлении максимальных значений. Соответствующие профили фотонов с энергиями (12-25) keV показывают более продолжительный по времени интервал с максимальными значениями, что наиболее характерно для изменений интенсивности вспышечной эмиссии в короне. В большинстве событий пиковые значения для (12-25) keV наступают несколько позже максимумов в профилях (50-100) keV. Согласно наблюдениям, наиболее вероятным источником количественного усиления вспышечных фотонов с энергиями (12-25) keV являются результаты тормозного излучения яркой вспышечной эмиссии в области короны, а для фотонов с энергиями (50-100) keV – в области фотосферы и температурного минимума.

Ключевые слова: солнечные вспышки, яркая эмиссия плазмы, корональные выбросы массы, рентгеновское и гамма-излучение.

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