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ENERGY SPECTRA OF SOLAR FLARE GAMMA-RAY EMISSION IN THE RANGE 0.03–2 GEV REGISTERED BY GAMMA–1 TELESCOPE

N. G. Leikov,* V. V. Akimov,* V. A. Volsenskaya,*
L. F. Kalinkin,* V. E. Nesterov,* A. M. Galper,**
V. M. Zemskoy,** Y. V. Ozerov,** N. P. Topchiev,***
M. I. Fradkin,*** E. I. Chuikin,† V. Y. Tugaenko, ‡
M. Gros, § I. Grenier, § A. R. Bazer-Bachi, ||
J.-M. Lavigne || and J.-F. Olive ||

** Space Research Institute of the Academy of Sciences of the RF, Profsoyuznaya 84/32, 117810, Moscow, RF, Russia*
*** Moscow Physical Engineering Institute, Kashirskoe shosse 31, 115409, Moscow, RF, Russia*
**** Lebedev Physical Institute of the Academy of Sciences of the RF, Leninsky Prospect 53, 117924, Moscow, RF, Russia*
† Ioffe Physical and Technical Institute of the Academy of Sciences of the USSR, Polytechnicheskaya 26, 194021, St. Petersburg, RF, Russia
‡ NPO "Energia", Kaliningrad, Moscow Region, RF, Russia
§ Centre d'Etudes Nucleaires, 91191, Saclay, France
|| Centre d'Etude Spatiales des Rayonnements, 31029, Toulouse, France

ABSTRACT

The gamma-ray telescope GAMMA-1 has registered gamma-emission in the range 30 - 2000 MeV from two solar flares. Spectral analysis with the use of maximum likelihood and maximum entropy methods has revealed the difference of gamma-ray production mechanism. In contrast with impulsive March 26, 1991 event where high energy gamma-rays originate exclusively as a bremstrahlung of primary accelerated electrons, at the extended phase of June 15, 1991 flare mainly the decay of neutral pions is responsible for the observed gamma-emission. An average spectral index for primary nucleons was -3.6. Evolution of the spectra for both flares shows tendency to a decrease of the primary particles mean energies with time.

INTRODUCTION

We have already reported a discovery of solar flare gamma-ray emission extending to energies greater than 1 GeV. /1/. The gamma-telescope GAMMA-1 /2/ registered two solar flares with different temporal and spectral characteristics. The short impulsive event on 1991 March 26 was caught from its very beginning and followed to the end. Observation of the powerful 1991 June 15 flare started at its extended phase and lasted (with a break for the orbital night) for more than two hours. In this paper we present results of energy spectra deconvolution with the use of maximum likelihood and maximum entropy methods which involve real energy-spread-function of the telescope and spectrum of the latitude dependent background. The spectra evolution with time for both flares is examined.

OBSERVATION

Details of the experiment performance have been reported in /3/. Figure 1 shows the total counting rate of gamma-rays with energies above the instrumental threshold for the March 26 event. The main burst which started at 20:27:56 UT is split into two sub-peaks. The first one has a rise time of 2 s and duration of 5 s. The second one - 1.6 s and 6 s respectively. Non-statistical fluctuations can be seen in a period of about 1 min after the main peak.

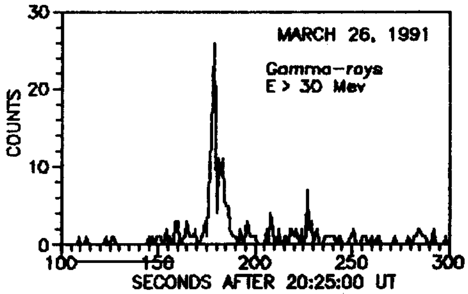

Fig.1: The total GAMMA-1 counting rate in the period of March 26, 1991 solar flare.

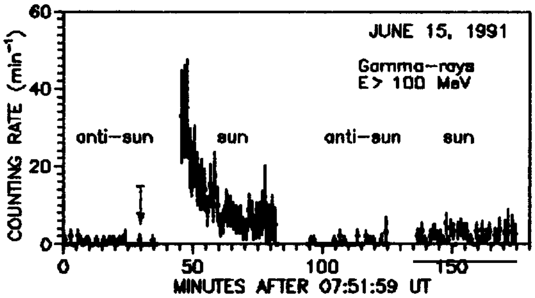

Fig.2: The Gamma-1 counting rate of photons with energies above 100 MeV in two orbits during the June 15, 1991 solar flare.

Available fragments of the June 15 flare in gamma-rays above 100 MeV are displayed in figure 2. In order to suppress the background strict selection criteria were applied /3/. During the Sun observations an orbital period (92 min) was shared between solar and antisolar orientations separated by the intervals of satellite slew when the telescope was off. The telescope was switched on in solar attitude at 08:37:22 UT 16 minutes later than maximum of emission in 1 - 8 A X-rays /4/ (marked by an arrow). In two orbits we followed continuous decrease of emission, then the telescope was switched off for a few days.

From 09:00:14 to 09:14:44 the satellite was traversing the South Atlantic Anomaly. In view of an uncertain background this interval was excluded from the spectral analysis.

METHOD OF SPECTRA ANALYSIS

The unknown source spectrum is connected with the observed numbers of counts $\vec{N}$ in an arbitrary binned space of measured energies through the instrumental convolution function $\vec{C}(E)$. Its essential components - effective area and energy-spread-function - were obtained by combination of an accelerator calibration and Monte-Carlo calculations./5/

The maximum likelihood method is applied with a use of Poissonian logarithmic likelihood function $L(\vec{N}, \vec{\mu})$, where the mean value $\vec{\mu}$ is a prediction from the energy spectrum model F(E):

$$\vec{\mu} = \vec{b} + \int_E F(E)\,\vec{C}(E)\,dE, \qquad (1)$$

where $\vec{b}$ is the background expectation. $L(\vec{N}, \vec{\mu})$ must be maximized over the spectrum model parameters.

Our approach implies several steps of analysis. At the first step we introduce the most simple power-low spectrum model ($F_0(E)$). Since the number of counts per bin at high energies may be small, the χ^2 statistics is inapplicable. Therefore we use for significance testing the nW^2 order statistics /6/. If the model $F_0(E)$ satisfies the data we proceed to a solution stability bootstrap testing, if not - possible spectral features must be searched for. For this purpose we use at the second step the maximum entropy approach /7/, which being applied to the problem of spectrum deconvolution suggests maximization of function

$$Q = \sum_i f_i(\ln [f_i/F_0(E_i)]-1) + \lambda\times L(\vec{N}, \vec{\mu}) \qquad (2)$$

over the values f_i which represent the source spectrum in many points E_i covering all the range of photon energies. First term in (2) is a relative entropy, where $F_0(E)$ is a solution at the preceding step of analysis. Varying iteratively the Lagrange multiplier λ we reach the 95% confidence boundary and so obtain the most regular spectrum which still more or less satisfies the data. This solution gives us a hint what kind of the spectrum model ($F_1(E)$) should be introduced in (1) for better agreement with the data. Further we use $F_1(E)$ as a probe in order to investigate the area of possible solutions by multiple bootstrap sampling.

RESULTS

MARCH 26, 1991 EVENT

Spectral characteristics of the March 26 solar flare were analyzed in two time intervals : main peak (20:27:56 - 20:28:07 UT) and trailer (20:28:07 - 20:29:20 UT). Owing to an evident identity of the measured energy distributions for two sub-peaks they were considered together. For both intervals a simple power-low spectrum model agrees well with the data. For the main peak the best likelihood fit gives an exponent 2.9 ± 0.2 and for the trailer 4.1 ± 0.4. At the confidence level of about 3σ we can see the softening of emission in trailer. In order to check the solution stability one more degree of freedom was added to the model (logarithmic parabola). Results of bootstrap testing are displayed in figure 3. Shaded area corresponds to a 68% - confidence region of possible solutions. One can see that the data really support the power-law model for both the main peak and trailer. Despite the lack of counts between 300 MeV and 1 GeV two photons with energies above 1 GeV registered in the peak correspond to the power-law extrapolation.

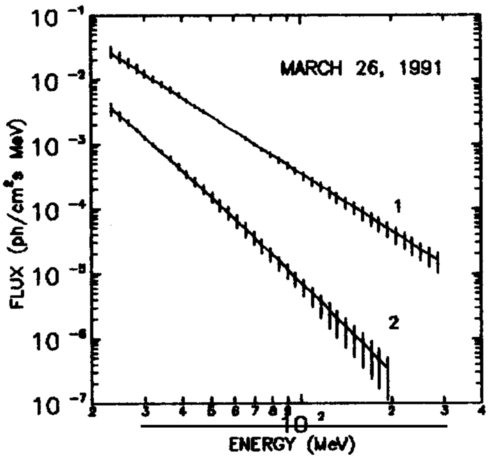

Fig.3. Differential gamma-ray spectra from the main phase (curve 1) and trailer (curve 2) of the March 26 solar flare.

JUNE 15, 1991 EVENT

In view of poor statistics in the second orbit where the June 15 flare gamma-emission was still distinguishable, only the 23-min period from the start of the Sun observation to the Anomaly entering was taken for the spectral analysis. The power-law model turned out to be completely inconsistent with the data. Figure 4 (solid curve) shows the maximum entropy solution which implies a spectrum bend somewhere near 100 MeV.

At the next step we examined the model

$$F_1(E) = A\times E^{-\gamma_1} \times [1 + (E/E_0)^2]^{-(\gamma_2-\gamma_1)/2} \quad (3)$$

which corresponds to a double-power-law spectrum with a smooth break at $E=E_0$ and exponents γ_1 at low and γ_2 at high energies. Though the solution is not too much sensitive to a value of E_0, formally the best fit can be reached with E_0 = 70 MeV. In the following analysis this value was fixed. Dashed curve in figure 4 represents the best fit with model (3) for the original data set. (γ_1=-6.3±1.4, γ_2=3.6±0.2). Figure 5 displays the best fits for three consecutive time intervals containing equal total numbers of photons. In general the spectrum shape is stable but values of the exponent at high energies (γ_2) show a tendency to a spectrum softening : first interval - 3.1 ± 0.4, second - 3.8 ± 0.6, third - 4.3 ± 0.6.

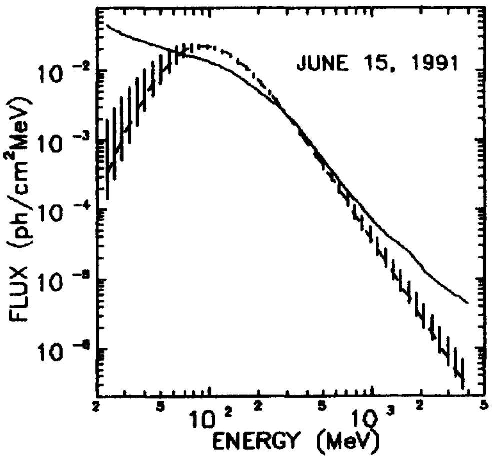

Fig.4 Differential gamma-ray spectrum from the extended phase of June 15 solar flare.

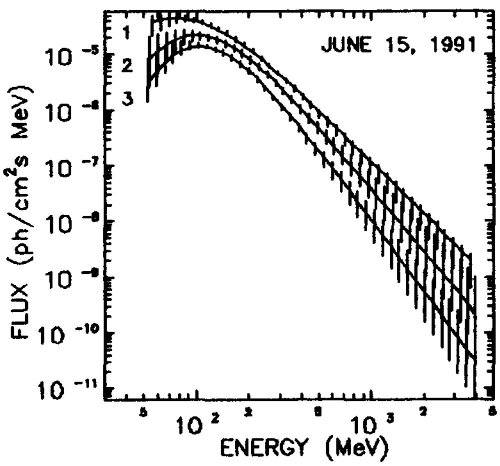

Fig.5. Evolution of the June 15 gamma-ray spectrum. Curves 1,2,3 - best fits with the double-power-law model for three consecutive time intervals.

DISCUSSION

We have shown a principal difference of spectral characteristics for two observed solar flares.

A pure power-law spectrum for the March 26 event strongly suggests that gamma-rays up to GeV energies originate as a bremstrahlung of primary accelerated electrons.

Flat spectrum near 100 MeV at the June 15 event gives an evidence for pion production at the extended phase of the flare. To explain sharp decrease of intensity at energies <70 MeV one has to suppose an attenuation of charged pions deposit into γ-ray flux which can be understood as a result of anisotropic emission in the magnetic loop studied in detail in /8/. Since at energies of several hundreds MeV neutral-pion-decay photons follow the spectrum of primary nuclei we can conclude that this spectrum had average index of 3.6.

For both flares the energy spectra show typical tendency of softening with the decrease of intensity.

An acceleration of nuclei to GeV energies in this flare is confirmed by the data of neutron monitors which showed at 8:37 - 8:40 an increase of neutron flux caused by the arrival to the Earth of 0.5 - 5 GeV nuclei /9/.

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