ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES



*Astron. Astrophys. Suppl. Ser.* **97**, 345-348 (1993)

# Spectral characteristics of high energy gamma ray solar flares

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*Received June 3; accepted August 31, 1992*

**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 differences in gamma-ray production mechanisms. In the impulsive March 26, 1991 event high energy gamma-rays originate exclusively as a bremsstrahlung of primary accelerated electrons. In contrast, the gamma ray emission of the extended phase of June 15, 1991 flare is mainly due to the decay of neutral pions. The 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.

**Key words:** solar flares, gamma-ray, data analysis.

## 1. Introduction.

We have already reported a discovery of solar flare gamma-ray emission extending to energies greater than 1 GeV (Akimov *et al.* 1991a). The gamma-telescope GAMMA-1 (Akimov *et al.* 1988a) 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. This results in differences in the spectral indexes reported earlier. The spectra evolution with time for both flares is examined.

## 2. Observations.

Details of the experiment performance have been reported by Akimov *et al.* (1991b). Figure 1 shows the counting rate of gamma-rays 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 sec and a duration of 5 sec. The second one - 1.6 sec and 6 sec, respectively. Non-statistical fluctuations can be seen for about 1 min after the main peak. Figure 2 shows the June 15 flare in gamma-rays above 100 MeV. In order to decrease the background a strict selection criterion was applied (Akimov *et al.* 1991b). During the Sun observations the orbits were shared between solar and antisolar orientations of the satellite. The telescope was switched on in solar attitude at 08:37:22 UT, 16 minutes after the maximum of emission in 1 - 8 Å X-rays (marked by an arrow). We followed the continuous decrease of emission over two orbits, then the background returned to its usual level.

From 09:00:14 to 09:14:44 the satellite was crossing the South Atlantic Anomaly. Hence, this interval was excluded from the spectral analysis.

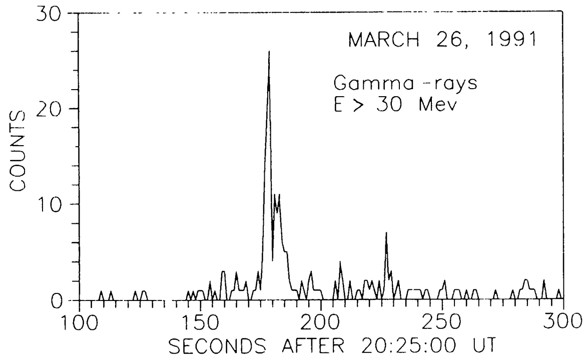


FIGURE 1. The total GAMMA-1 counting rate in the period of March 26, 1991 solar flare.

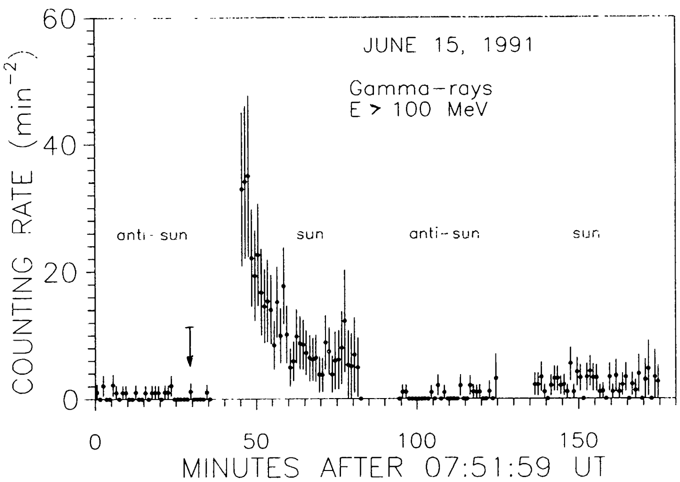


FIGURE 2. The Gamma-1 counting rate of photons with energies above 100 MeV in two orbits during the June 15, 1991 solar flare. An arrow denotes the maximum of soft X-ray emission.

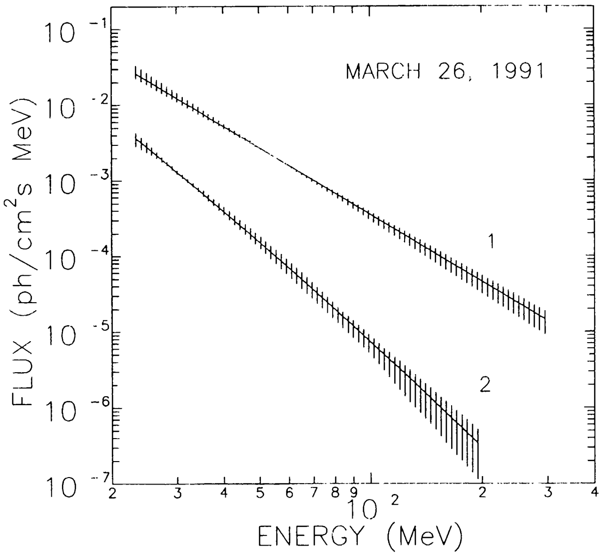


FIGURE 3. Differential gamma-ray spectra from the main phase (curve 1) and trailer (curve 2) of the March 26 solar flare as it follows from the logarithmic parabola model. Shaded area contains 68% of the bootstrap test solutions.

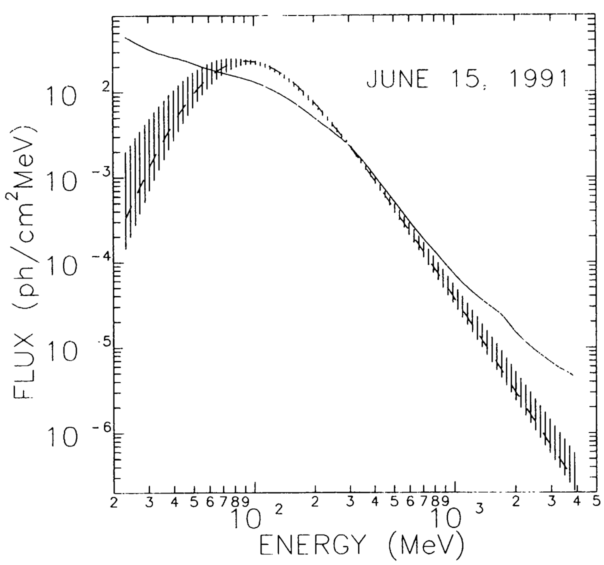


FIGURE 4. Differential gamma-ray spectrum from the extended phase of June 15 solar flare (08:37:22 - 09:00:14 UT). Solid curve - the maximum entropy solution, dashed curve - best fit with the double-power-law spectrum model. Shaded area - the same as in figure 3.

## 3. Method of spectra analysis.

The unknown source spectrum is connected with the observed number of counts **N** in an arbitrary binned space of measured energies through the instrumental convolution function **C** $(E)$. Its essential components - effective area and energy-spread-function - were obtained by combination of an accelerator calibration and Monte-Carlo calculations (Akimov *et al.* 1988b). The maximum likelihood method is applied using a Poissonian logarithmic likelihood function $L$ (**N**, $\mu$), where the mean value $\mu$ is a prediction from the energy spectrum model $F(E)$:

$$\mu = \mathbf{b} + \int_E F(E)\,\mathbf{C}\,(E)\,\mathrm{d}E, \qquad (1)$$

where **b** is the background expectation. $L(\mathbf{N}, \boldsymbol{\mu})$ must be maximized over the spectrum model parameters. Several steps of analysis are involved. At the first step we introduce a simple power-law spectrum model ($F_0$ $(E)$), and set a marginal 95% - confidence level. Since the number of counts per bin at high energies may be small, the $\chi^2$ statistics is inapplicable. Therefore we use the $nW^2$ order statistics (Kendall & Stuart 1967). 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 (Cornwell & Evans 1985), which, being applied to the problem of spectrum deconvolution, suggests maximization of the function

$$Q = \sum_i f_i \left(\ln [f_i/F_0 (E_i)] - 1 \right. + \lambda * L(\mathbf{N}, \boldsymbol{\mu}) \quad (2)$$

over the values $f_i$ which represent the source spectrum in many points $E_i$ covering all the range of photon energies. The first term in (2) is relative entropy, where $F_0$ $(E)$ is a solution at the preceding step. Varying iteratively the Lagrange multiplier $\lambda$ *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 to what kind of spectrum model ($F_1$ $(E)$) may 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.

## 4. Results.

### 4.1. March 26, 1991 event.

The spectral characteristics of the March 26 solar flare were analyzed in two time intervals: the main peak (20:27:56 - 20:28:07 UT) and the trailer (20:28:07 - 20:29:20 UT). For both intervals a simple power-law model agrees well with the data. For the main peak the best likelihood fit gives an exponent of -2.95 ± 0.23 and for the trailer -4.13 ± 0.37. As a confidence level of about $3\sigma$ we can see the softening of emission in the trailer. In order to check the solution stability one more degree of freedom was added to the model (logarithmic parabola). The results of bootstrap testing are shown in Fig. 3. The 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.

### 4.2. June 15, 1991 event.

Because of the poor statistics in the second orbit where the gamma-emission was still distinguishable, only the 23-min period from the start of Sun observation to the Anomaly entering was considered 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 is the most regular one among all possible spectra with a chance probability to generate the observed data set not less than 5%. This non parametrical solution implies a spectral bend somewhere near 100 MeV. So, in order to get a better agreement with the data, at the next step we examined the model:

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

which corresponds to a double-power-law spectrum with a smooth break at $E = E_0$ and exponents $\gamma_1$ at low and $\gamma_2$ 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. The dashed curve in Fig. 4 represents the best fit with model (3) for the original data set. ($\gamma_1 = -6.3 \pm 1.4$, $\gamma_2 = 3.64 \pm 0.24$). Figure 5 displays the best fits for three consecutive time intervals containing an equal total number of photons. In general the spectral shape is stable but values of the exponent at high energies ($\gamma_2$)show a tendency to a spectrum softening: first interval - 3.13 ±0.37; second - 3.75 ±0.55; third - 4.31 ±0.57.

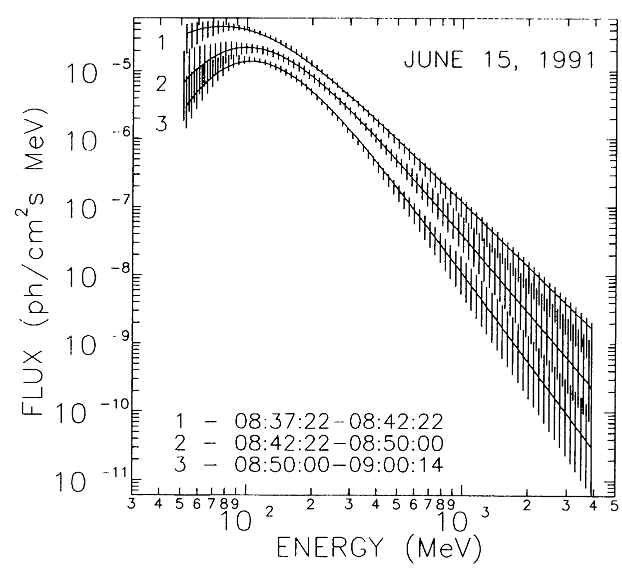


FIGURE 5. Evolution of the June 15 gamma-ray spectrum. Curves 1,2,3 - best fits with the double-power-law model for three consecutive time intervals.

## 5. Discussion.

In the present more comprehensive analysis, we have revised the preliminary spectra presented by Akimov *et al.*

(1991a), where no attempts of deconvolution had been made. The results obtained allow to confirm the earlier supposition concerning the difference of photon production mechanims in the two observed solar flares. A pure power law spectrum for the March 26th event strongly suggests that gamma rays up to a least 300 Mev originate as a bremsstrahlung of primary accelerated electrons. The flat spectrum near 100 MeV for the June 15 event is to be considered as an evidence for pion production at the extended phase of the flare and thus as a confirmation of results reported by Forrest *et al.* (1985). The data also denote a possible suppression of the gamma ray emission at lower energies, where the contribution of charged pions expected for isotropic distribution become dominating. This can be explained as a result of anisotropic emission in a solar flare magnetic loop, treated in detail by Mandzhavidze & Ramaty (1992). Since at energies of several hundred MeV neutral-pion-decay photons follow the spectrum of primary nucleons we can expect that this spectrum had average index of -3.6 and was possibly softening in time.

**Acknowledgements.**

This work was supported for the French part by CNES (Centre National d'Etudes Spatiales).

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