High-energy gamma-ray emission of solar flares as an indicator of acceleration of high-energy protons

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***Abstract*. High-energy (>100 MeV) gamma-ray emission was observed by the SONG instrument within CORONAS-F satellite mission during the four solar flares namely 25 August 2001, 28 October 2003, 4 November 2003, and 20 January 2005. Gamma-ray emission spectra were restored. All of the spectra possessed the same characteristic feature associated with generation and decay of neutral pions. This common feature enabled a highly accurate definition of the time interval of the appearance of protons accelerated above energies 300 MeV in the solar atmosphere and estimation of the fluxes of high-energy gamma-ray emission.**

***Keywords*: solar flares, gamma-ray emission, accelerated protons**

I. Introduction

The potential value of gamma-ray and neutron measurements to be a probe of energetic ions accelerated in solar flares was pointed out by Lingenfelter and Ramaty [1]. These calculations showed that neutrons detected at 1 AU and gamma-rays from $\pi^{\pm}$ and π^0 decay could be directly related to very energetic ions, because of the high threshold kinetic energy required for their production ($\sim$ 300 MeV for π's and neutrons in $p-p$ reactions and $\sim$ 200 MeV in $p-\alpha$ reactions). Four gamma-ray-emission events with high energies were recorded by the SONG instrument onboard the CORONAS-F satellite. The SONG (SOlar Neutrons and Gamma-rays) detector had a CsI(Tl) crystal of size ø20 cm × 10 cm surrounded by a plastic scintillator shield. The flares of 28 October 2003 and of 20 January 2005 were studied in detail in [2], [3], [4]. In the present communication we address mainly observations of the flares of 25 August 2001 and of 4 November 2003.

II. Flare of 25 August 2001

The 3B/X5.3 solar flare that occurred at heliographic coordinates S17 E34 on 25 August 2001 commencing at 16:24 UT was the source of a number of energetic phenomena including intense sub mm radioemission, X-ray, neutrons and gamma-ray emissions created by the ions accelerated up to 300 MeV. An impulse phase of this flare lasted only for few minutes as can be seen in upper panel of Fig. 1. SXR emission measured by GOES-10 in two energy bands 2-12 Å and 0.5-4 Å is presented in this panel together with the temporal derivative of the flux in

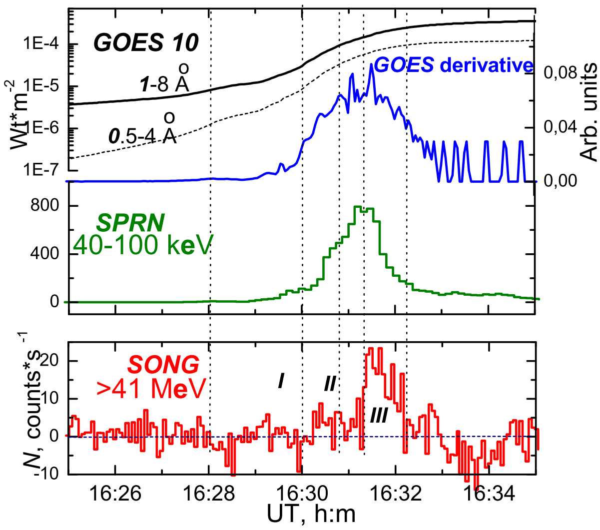

Fig. 1. Observations of X-ray and Gamma-Ray Emissions of the Solar Flare of 25 August 2001.

the 0.5-4 Å band. The hard X-ray emission (40-100 keV) recorded onboard the CORONAS-F by SPRN detector [5] is depicted in the middle panel of Fig.1. A close similarity of these two curves indicates the connection between hard and soft X-ray emissions according to the Neupert effect [6] that suggests that soft X-ray emitting plasma was "evaporated" due to bombardment of the chromosphere by electrons and protons, which produced the observed hard X-ray emission.

The net count rate of high-energy gamma-emission recorded by the SONG is presented in the bottom panel. A sharp increase of the high-energy gamma-emission intensity was close to the maximum of SXR derivative which in its turn suggests that the most effective acceleration of particles occurred during short period of the main energy release.

Vertical lines in Fig. 1 mark time intervals selected to restore spectra. Borders of these intervals are 16:28:00 - 16:30:02 UT (interval I), 16:30:02 - 16:30:44 (II) and 16:31:18 - 16:32:10 (III). In order to analyze in detail time dependent gamma-ray spectral variations, we fitted the SONG count rate spectra accumulated over these time intervals with simulated deposited energy spectra generated with the help of the GEANT3.21 code. For each spectrum, we used a two-component model including a continuum produced mainly by primary-

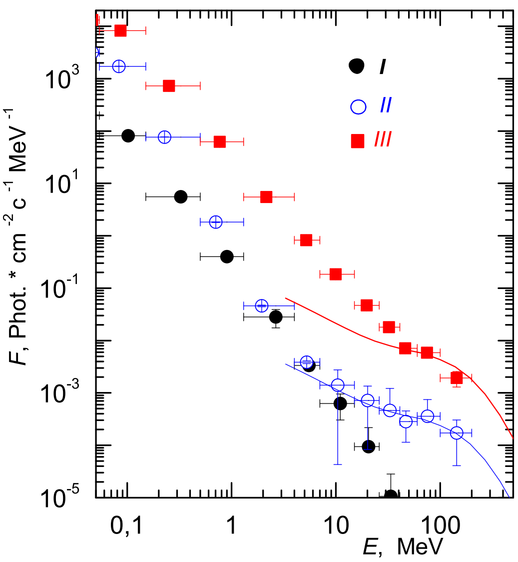

Fig. 2. Gamma-Ray Emission Spectra of the Flare of 25 August 2001.

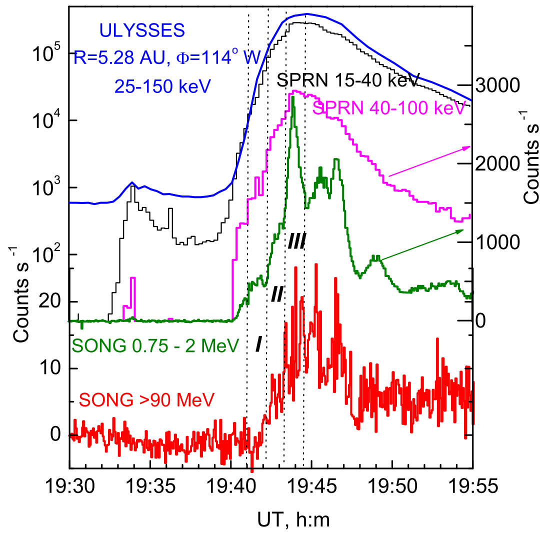

Fig. 3. Observations of X-ray and Gamma-Ray Emissions of the Solar Flare of 4 November 2003.

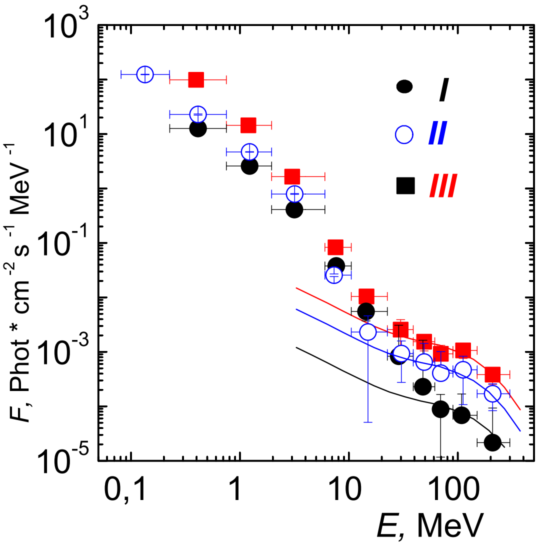

Fig. 4. Gamma-Ray Emission Spectra of the Flare of 4 November 2003.

accelerated electrons and a pion-decay component. The latter was used in the form of a broad 'line' caused by the neutral pion decay, peaking at 67 MeV, plus a continuum related to bremsstrahlung from electrons and positrons produced in the charged pion decay process [7]. The resulting background-subtracted time-integrated spectra are presented in Fig. 2. Solid curves in Fig. 2 and 4 represent the calculated spectra of gamma-ray emission produced by pion decay.

Ground level enhancement (GLE) was not observed in this event but solar neutrons were detected by SONG [8] and by the neutron monitor (NM) Chacaltaya [9].

III. Flare of 4 November 2003 (3B, S19 W83)

The hard X-ray and gamma-ray emission from the "giant" solar flare on 4 November 2003 was observed by SONG (19:40-19:58 UT). It was not certain whether this time interval coincided with the impulse phase of the flare because the Hα flare was located at the limb and the associated soft X-ray emission observed by GOES reached saturation at 19:43-19:58 UT. Fortunately Ulysses located on the side of the Sun-Earth line [10] detected an increase in 25-150 keV non-thermal X-ray emission in the interval 19:33-20:15 UT with the maximum at 19:44 UT, almost coinciding in time with the maximum of the SONG observations. Data in Fig. 3 show that the X- and gamma-ray emission observed by SONG covered for the most time of the main flare energy release. Ulysses data were re-calculated to 1 AU. Vertical lines in Fig. 3 mark time intervals selected to restore spectra. Borders of these intervals are 19:41:00-19:42:00 UT (interval I), 19:42:00-19:43:00 (II) and 19:43:00-19:44:20 (III).

Fig. 4 shows background-subtracted time-integrated spectra of gamma-ray emission. The pion-decay spectrum is a satisfactory fit to spectra II, III, characterized by the significant flattening below ~70 MeV. During the interval I the pion-decay emission was absent or weak.

GLE was not observed in this event although fluxes of solar protons with energies >300 MeV were detected both by GOES and by CORONAS-F. An intensive flux of solar neutrons was detected by SONG [8] and by the NM's Mexico and Haleakala [9].

IV. Discussion

Fluxes of X- and gamma-ray emission recorded by CORONAS-F in course of the solar flares of 28 October 2003 (see Fig. 5) and of 20 January 2005 (Fig. 6) exhibited dynamics similar to one observed in course of

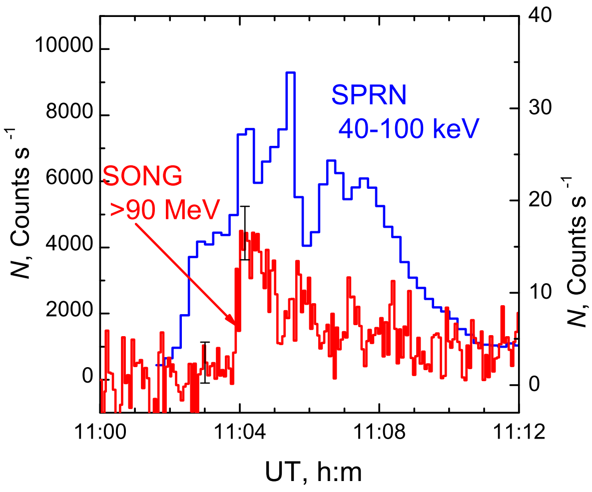

Fig. 5. X-ray and Gamma-Ray Emission of the Solar Flare of 28 October 2003

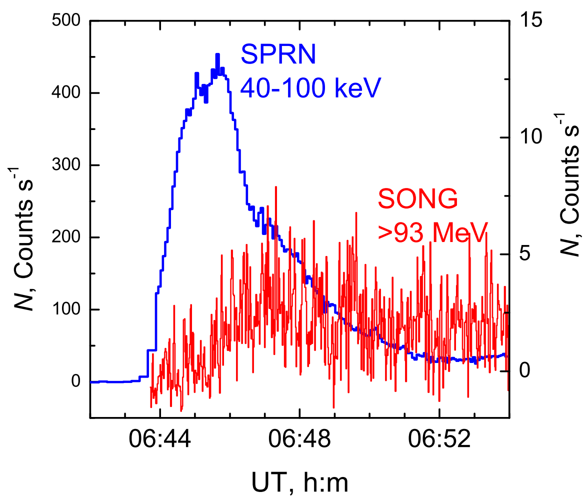

Fig. 6. X-ray and Gamma-Ray Emission of the Solar Flares of 20 January 2005.

the flares of 25 August 2001 and of 4 November 2003. Right scales in these Figs. correspond to the SONG data. Spectral analysis revealed an appearance of pion-decay gamma emission during both these flares [2], [4]. On 28 October 2003 such an emission beginning at 11:02 was absent or weak but increased drastically by 11:03:51 UT. On 20 January 2005 the pion-decay gamma emission was recorded right from the beginning of the flare and intensity of the emission greatly increased at 06:45:34.

Solar neutrons were detected by SONG [8] and by the NM Tsumeb [11] in course of the 28 October 2003 event. No solar neutrons were detected on 20 January 2005. Characteristics of the flares under considerations are presented in Table 1.

Having processed the response of the SONG instrument to the emissions of the four flares, we divided the first flare phase (usually called an impulse phase) into two intervals.

A) The bremsstrahlung generated by primary accelerated electrons dominated within the first interval with duration 1-2 min. The bremsstrahlung spectrum extended up to 60-100 MeV. Protons accelerated to energies exceeding 10 MeV generated nuclear de-excitation gamma-ray lines and the 2.223 MeV line emission, which were recorded by SPI/INTEGRAL (28 October 2003) and by RHESSI (20 January 2005). SONG measured the 2.223 MeV line emission as well. During this interval, the pion-decay emission was absent or weak as was in the 4 November 2003 and 20 January 2005 flares.

B) The second time interval with the duration of 4-6 min was characterized by a sharp increase of the gamma-ray produced by the decay of neutral pions. The increase of the high-energy emission was most likely due to interactions in the solar atmosphere of high-energy protons, a large number of which underwent strong acceleration up to energies exceeding 300 MeV, with an ambient matter of the solar atmosphere. Electrons also underwent an additional acceleration on a short timescale ($\sim$2-4 s) at the beginning of interval B. The maximum flux of the pion-decay gamma-ray emission at 100 MeV and the start times of the detection gamma emission with energy $>$100 MeV by SONG are summarized in Table 1.

C) We also define an 'extended phase' - or decay phase of the flares with the pion-decay emission. High-energy emissions lasted until the end of our measurements, at least 7-8 min, with a weak sign of variability (see Fig. 3, 5, and 6).

The appearance of high-energy protons in the corona is evidenced by the commencement of the pion-decay component, which is determined with an accuracy of few seconds. Such a determination of onset time of proton acceleration gives us a solid time rule for GLE studies and permits to estimate energies of solar neutrons from their time-of-flight.

We emphasize that just the detection of the gamma-ray emission produced by the decay of neutral pions provides the most accurate and direct way to determine, at least, the onset of the proton acceleration to hundreds of MeV and higher energy, because the alternate process, which could imitate the corresponding spectral feature, is not known to exist. Other methods of determination of the start of the acceleration of heavy particles (analysis of radio emission, the motion of CMEs, the arrival times of particles at Earth) are all indirect. They provide ambiguous and sometimes contradictory results.

V. Conclusions

1. High-energy ($>$100 MeV) gamma-ray emission was observed by the SONG instrument during the four solar flares namely 25 August 2001, 28 October 2003,

TABLE I
MAJOR SOLAR FLARES OBSERVED BY SONG/CORONAS-F.

Date	Location/Importance	Onset of pion-decay gamma emission, UT	Gamma-ray flux at 100 MeV, $MeV^{-1}cm^{-2}s^{-1}$	Particles
25 August 2001	S17E34, 3B/X5.3	16:30:16±2 s	$7.3 \cdot 10^{-4}$	n
28 October 2003	S16E08, 4B/X17.2	11:03:51±2 s	$6.8 \cdot 10^{-3}$	GLE65, n
04 November 2003	S19W83, X28.9	19:42:38±4 s	$1.0 \cdot 10^{-3}$	n
20 January 2005	N14W61, 3B/X7.1	06:45:34±4 s	$3.6 \cdot 10^{-3}$	GLE69

4 November 2003, and 20 January 2005. These observations were unique in course of the 23rd solar activity cycle.

2. The spectral feature caused by the neutral pion decay was derived in all these flares and the time moments of an appearance of this feature were determined. This fact permits to find onset times of high-energy proton release. Note that fluxes of high-energy solar particles (protons and/or neutrons) were detected at the Earth in all of the events under consideration.

VI. ACKNOWLEDGEMENT

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