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THE MUON BURSTS WITH ENERGY ABOVE 200 GEV RECORDED DURING GLE EVENTS

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Introduction

The most energetic particles of Solar Cosmic Rays (SCR) are generated on the Sun during powerful flares and processes accompanying them [1, 2]. The registration of solar particles from the flares with greatest possible energy achievable on the Sun is one of the major observational tasks in the problem of SCR generation [3, 4]. The data of the muons' registration with energy ≥200 GeV at the Baksan Underground Scintillation Telescope (BUST) are used in searching for SCR with energy >500 GeV. 35 GLE events have occurred during the BUST operation since April 1981 up to present. The data of the muons registration at the BUST are available in 34 cases. 19 GLE events of the 22nd solar activity cycle and of the end of 21st were investigated earlier [5, 6]. 15 new GLE events, which occurred from 1997 up to 2005, are added now. The results of the statistical analysis of all 34 GLE events are briefly presented below.

Baksan underground scintillation telescope

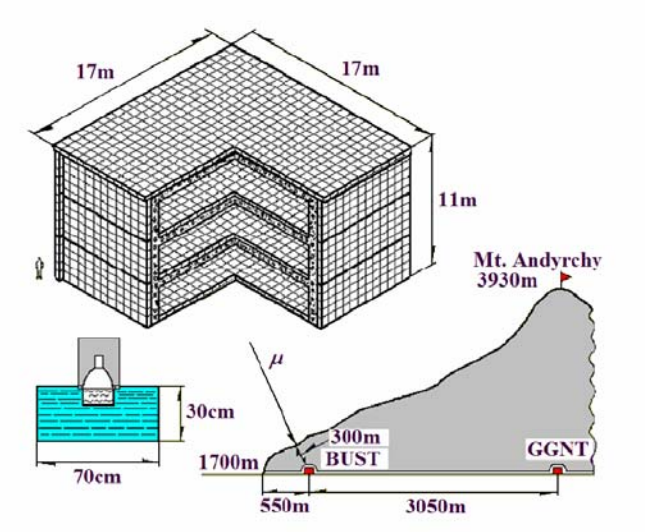

Fig.1. The BUST consists of 3150 detectors with volume 70×70×30 cm^3 filled with liquid scintillator.

Geographic coordinates of BUST are 43.28°N, 42.69°E. The effective depth into a ground makes up 850 m of water equivalent. The angular resolution on average makes up ≈2º. The telescope has an effective area of 200 m^2. The threshold energy of muons is E_μ=200 GeV. The minimum energy of primary protons is E_p=500 GeV.

Method of analysis

In searching for the muon bursts at the BUST we used the method of analysis developed earlier [5, 6] for study of the GLE events of 21st and 22nd cycles [7, 8]. The uniform method provides receiving a homogeneous series of data, which, in turn, allows to correctly compare the properties of events of different cycles. Minimal energy of single muons registered at the BUST makes up to ≥200 GeV. Primary protons in this case have energy >500 GeV. It exceeds approximately 100 times the energy of SCRs, which are usually registered by the neutron monitors on the Earth's surface. Muons are registered by the BUST as trajectory events and they are summarized in angular distribution during each 15-minutes interval. The search for probable signals is carried out in a 3-hour interval during each flare (1 hour before a maximum of X-ray flare and 2 hours after that) within angular cells with 10°×15° in size over a zenith angle and over an azimuth, respectively.

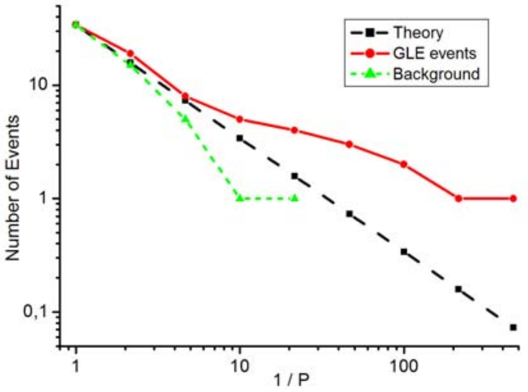

Fig. 2. The integral distribution, N(1/p), of muon bursts, which were found at the BUST during the GLE events of 21-23 solar activity cycles (1981-2005).

The cells are mutually overlapped in such a way that there were no losses of a probable signal along the edges of cells. The total number of cells is 680. Only one maximal burst for every GLE event is selected from all the found excesses above the background (in any cell, in any 15-minute interval within 3 hours).

Such bursts were considered candidates for the probable signals of SCR and they were subjected to the further analysis. The delay of the onset of the muon burst relative to the maximum of X-ray flare was calculated for each of 34 selected bursts. For the center of angular cell, in which the muon burst was found, the zenith angle and the azimuth were evaluated in the ecliptic longitude and latitude. The probability *P(3h)* of random realization of a burst due to fluctuations in any of 680 angular cells during 3 hours was calculated using the magnitude of excess above the average background of galactic cosmic rays (GCR):

$$P(3h) = 1 - e^{-n\cdot w}, \qquad (1)$$

where: $n = 680\times12 = 8160$ is the total number of angular cells and time intervals, and w – Poisson probability of the burst with a given magnitude. The value of *P(3h)* was used then for the definition of statistical significance of the burst (Fig. 2 and Fig. 3).

The integral distribution of the bursts number versus *1/P(3h)* is depicted in Fig. 2. The total number of bursts having probability not exceeding the given *P(3h)* (integration from *1/P* up to + ∞) is shown at each point. Circles represent the distribution for the bursts found during GLE events. Squares correspond to the theoretically expected distribution. Triangles are related to the distribution for the bursts from the background intervals.

The 3-hour intervals distanced 1 day before or after the corresponding flare were used as background intervals. The selection of bursts within those intervals was made by the same method as during GLE events.

The integral distribution of events *N(1/P)* for a purely random process (Poisson, Gauss, etc.) in double logarithmic scale presents a direct line with a slope $k = -1$ (as a corollary of the law of big numbers) [9, 10]. The probability distribution for the bursts recorded during GLE events differs significantly from the theoretically expected distribution and from the distribution for background intervals. The observed surplus of bursts of large amplitude possibly indicates that there is an additional muon flux. For background intervals there is a good agreement of experiment with the theoretically expected distribution. Figure 2 also demonstrates distinctly that the distribution of muon bursts during GLE differs from Poisson's. Therefore, more important is the probability, where the differences of experiment from background and from theory began, namely from $P\approx0.1$. From this position, it is possible to regard as significant only four bursts: 29 September 1989, 28 October 2003, 15 June 1991 and 12 October 1981.

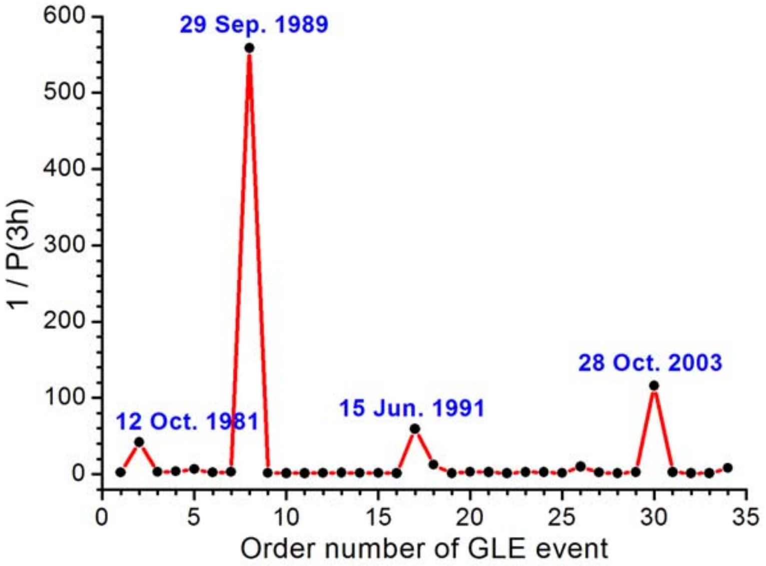

Fig. 3. Significance of the muon bursts recorded at the BUST during 1981-2005.

Table 1. The main properties of the most significant muon bursts, which were found at the BUST during GLE events.

Date of GLE	Amplitude, σ	Poisson probability	P(3h)	Delay	λ	β
Oct 12, 1981	5.0	$2.9 * 10^{-6}$	0.0240	69 min	59° W	10° N
Sep 29, 1989	5.5	$2.2*10^{-7}$	0.0018	117 min	42° W	72° N
Jun 15, 1991	5.0	$2.1*10^{-6}$	0.0170	99 min	20° W	51° N
Oct 28, 2003	5.1	$1.1*10^{-6}$	0.0086	120 min	127° W	66° N

Main properties: a) short duration is (≤ 15 min); b) small solid angle is (10º×15º cell); c) delay from the maximum of X-ray flare is by 1-2 hours; d) minimal energy of protons is $E_P \geq 500$ GeV.

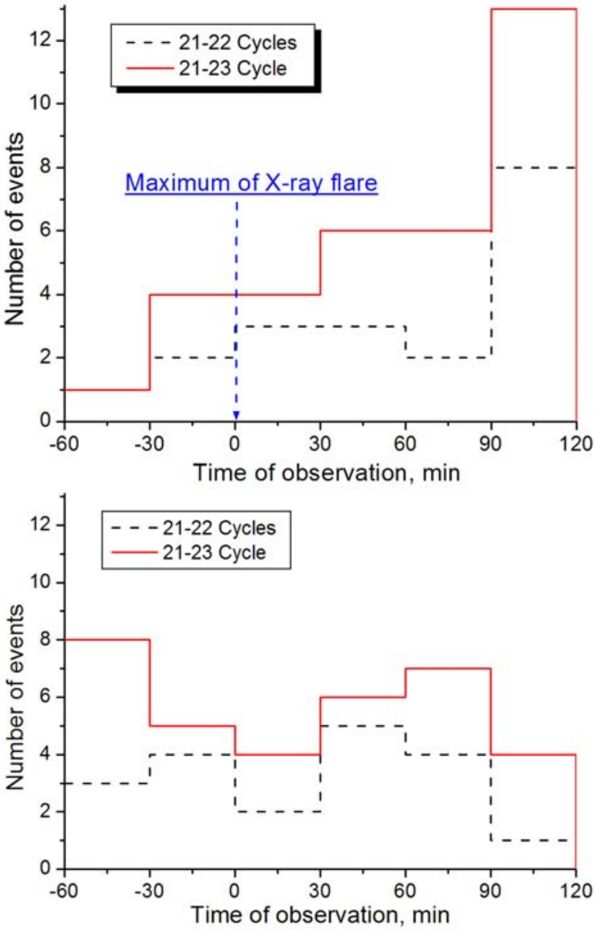

Fig. 4. The temporal properties of the muon bursts. Top panel illustrates the bursts' distribution inside a 3-hour interval of observation during GLE events. Bottom panel illustrates the distribution of bursts for the background intervals.

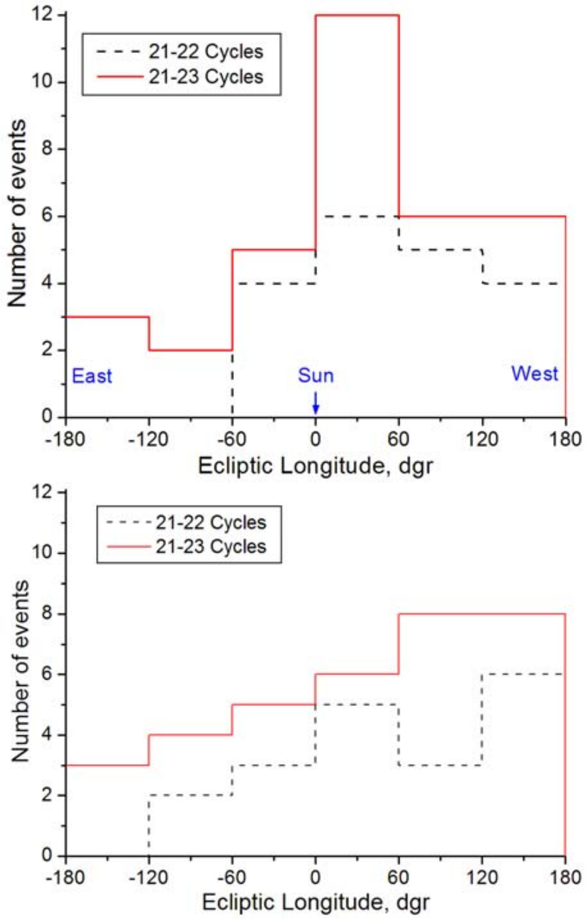

Fig. 5. The spatial properties of the muon bursts. Top panel illustrates the bursts' distribution over the ecliptic longitude during GLE events. Bottom panel illustrates the distribution of bursts for background intervals.

The above four muon bursts are obviously distinguished by the importance (inverse value to probability of random imitation of burst due to fluctuations of the background, Fig. 3). Namely these bursts show some difference of integral distribution during GLE events (Fig. 2) from the theoretically expected and from the background distributions. The specified bursts can be considered as possible increases of SCRs with energy more 500 GeV.

Spatial and temporal properties of the muon bursts during GLE events also differ from the properties of the bursts from background intervals. The bursts' distribution inside 3-hour interval of observation is presented in Fig. 4. It is obvious that distribution kept an asymmetry, and the majority of bursts are observed within 1-2 hours after the maximum of X-ray flare. All four most significant bursts are also in this time interval. Temporal distribution of the bursts for background intervals is close to uniform distribution.

The bursts' distribution over ecliptic longitude is shown in Fig. 5. As in the previous 21-22 cycles, the majority of new bursts in the 23rd cycle were observed from directions within the longitudes range of 60°E – 180°W. The bursts distribution from background intervals also has a similar asymmetry. Hence, it is mainly due to the orientation of the sensitivity diagram of the BUST in these directions during GLE events. The exception is the interval 0° – 60° West of the Sun-Earth direction. The number of events in this interval differs appreciably from the background event number. The interval between 0° – 60°W contains more than a third of all bursts, including three out of the four most significant ones.

Conclusions

A considerable growth of statistics has given us an opportunity to select confidently four muon bursts, which cannot be explained by the background fluctuations. Moreover, by using new presentation of observational data in the form of integral distribution *N(1/P)*, we are able visually and quantitatively to determine the difference in numbers of the registered bursts and the theoretically expected ones. The majority of muon bursts are observed within 1-2 hours after the maximum of X-ray flare. The interval 0°– 60°W is remarkable for a large number of bursts in the distribution over ecliptic longitude. As to other intervals there is no essential difference from the background distribution. Observational characteristics of the four most significant bursts are similar; in particular, they have the same spatial and temporal properties. Physical interpretation of the obtained results is rather a difficult task and it should be a subject of separate study.

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