29th International Cosmic Ray Conference Pune (2005) **1**, 197-200

The muon bursts with energy ≥200 GeV during GLE events of 21-23 solar activity cycles

S.N. Karpov[a], L.I. Miroshnichenko[b] and E.V. Vashenyuk[c]
(a) Baksan Neutrino Observatory, Institute for Nuclear Research of RAS, Neutrino, KBR 361609, Russia
(b) N.V. Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Waves Propagation (IZMIRAN), Troitsk, Moscow Region 142190, Russia
(c) Polar Geophysical Institute, Kola Science Center of RAS, Apatity, Murmansk Region 184209, Russia
Presenter: S.N. Karpov (karpovsn@yandex.ru), rus-karpov-SN-abs2-sh15-poster

Statistical analysis of the muon bursts with energy ≥200 GeV recorded at the Baksan Underground Scintillation Telescope (BUST) during GLE events is extended on the current 23rd cycle of solar activity. The observed surplus of bursts with large amplitude possibly indicates a presence of an additional muon flux. The muon bursts of significant amplitude were registered during four GLEs: 29 September 1989, 28 October 2003, 15 June 1991 and 12 October 1981. The temporal distribution of the newly occurred bursts shows the asymmetry found earlier: the delay of the bursts relative to maximum of corresponding X-ray flare is equal to about 1-2 hours. The ecliptic longitude distribution of the bursts shows surplus in an interval 0° – 60° to the West from the Sun-Earth direction, which possibly indicates the link with the IMF.

1. Introduction

The most energetic particles (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]. The data of muons registration with energy ≥200 GeV at the Baksan Underground Scintillation Telescope (BUST) are used in searching for SCR with energy >500 GeV. Powerful flares with a hard SCR spectrum above 1 GeV are rather rare events [4]. Therefore the long continuous observations are necessary. The 35 GLE events have occurred during the BUST operation since April 1981 up to now. The data of the muons registration at the BUST are available in 34 cases. The 19 GLE events of the 22nd solar activity cycle and of the end of 21st one have been investigated earlier [5, 6]. The 15 new GLE events, which occurred from 1997 to 2005, are added now. Results of the statistical analysis of all of 34 GLE events are briefly presented below. Earlier similar analysis has been also carried out for 44 X-ray flares and for 38 solar proton events [7] in a maximum of activity of the current cycle (2000 – 2002).

2. Method of analysis

In searching for the muon bursts at the BUST we used the method of the analysis developed earlier for study of GLE events of 21st and 22nd cycles (in more details it has been described elsewhere [5, 6]). The uniform method provides receiving a homogeneous series of the data that, in turn, allows correctly comparing the properties of events of different cycles. Minimal energy of single muons registered at the BUST makes up ≥200 GeV. Primary protons in this case have energy >500 GeV. It is approximately 100 times more than energy of SCR, which are usually registered by the neutron monitors at the Earth's surface. Muons are registered by the BUST as the trajectory events and they are summarized in angular distribution during each 15-minutes interval. 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 of 10°×15° in size over a zenith angle and over an azimuth, respectively. The cells are mutually overlapped in such a way that there were no losses of a probable signal along the edges of the cells. Total number of cells is 680. Only one maximal burst for every GLE event is selected from all found excesses above a background (in any cell, in any 15-minute interval within 3 hours).

Such bursts were considered as candidates for the probable signals of SCR and they were undergone to the further analysis. The delay (or outstripping) of the onset of muon burst relative to a 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):

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

where $n = 680 \times 12 = 8160$ is 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. As shown below, only small number of the largest bursts cannot be explained by fluctuations of GCR background.

3. Main results

Integral distribution of the bursts number versus *1/P(3h)* is depicted in Figure 1. The total number of the bursts having probability not exceeding a given *P(3h)* (integration from *1/P* up to +∞) is shown in each point. Circles represent the distribution for the bursts found during GLE events, squares correspond to theoretically expected distribution, and triangles are related to the distribution for the bursts from the background intervals.

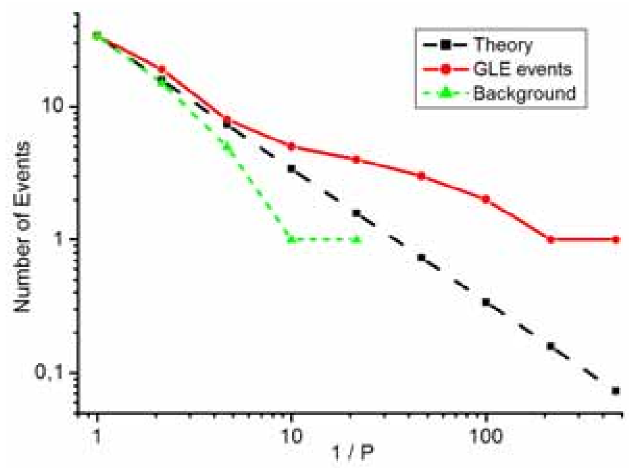

Figure 1. Integral distribution, *N(1/p)*, of muon bursts, which were found on the Baksan Underground Scintillation Telescope (BUST) during GLE events of 21-23 solar activity cycles (1981-2005). Circles represent the distribution for the bursts found during GLE events, squares correspond to theoretically expected distribution, and triangles are related to the distribution for the bursts from the background intervals.

The 3-hour intervals distanced on 1 day up to or after corresponding flare were used as the background intervals. Selection of the 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).

The probability distribution for the bursts recorded during GLE events significantly differs from theoretically expected distribution and from the distribution for background intervals. The observed surplus of bursts of large amplitude possibly indicates that an additional muon flux exists. For control intervals there is a good agreement of experiment with theoretically expected distribution. Figure 1 also demonstrates distinctly that distribution of muon bursts during GLE differs from Poisson one. Therefore, the absolute value of the burst probability *P(3h)* is less important than the probability where the differences of experiment from background and from theory begin, i.e. the probability $P \approx 0.1$ in our case. From this position it is possible to regard as significant four bursts only: 29 September 1989, 28 October 2003, 15 June 1991 and 12 October 1981

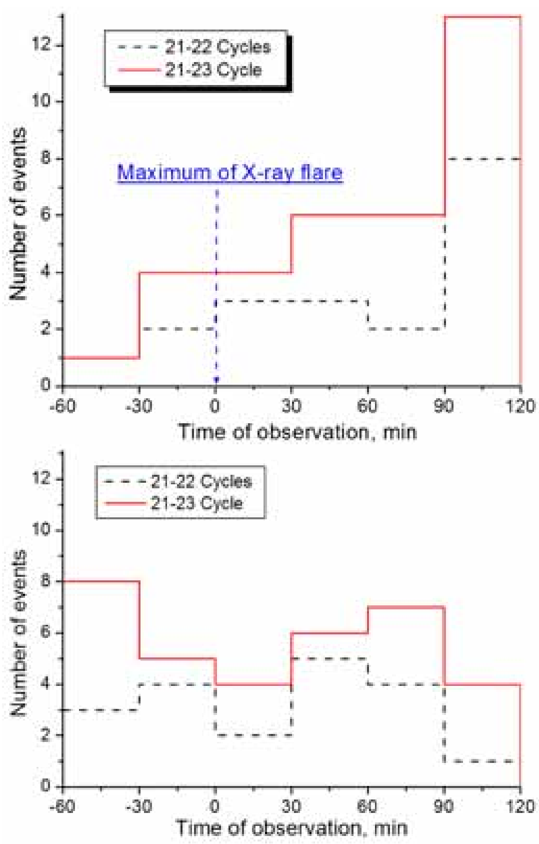

Figure 2. Temporal properties of muon bursts. The top panel – the bursts distribution inside 3-hour interval of observation during GLE events. The bottom panel – distribution of bursts for background intervals.

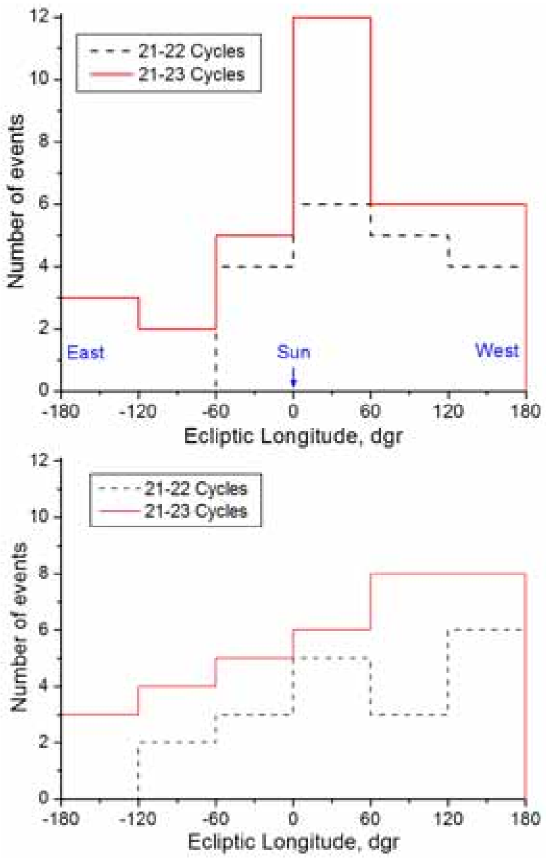

Figure 3. Spatial properties of muon bursts. The top panel – the bursts distribution over the ecliptic longitude during GLE events. The bottom panel – distribution of bursts for background intervals.

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

Figure 2. The dashed line shows the results obtained for the GLEs of 21-22 cycles of solar activity, solid line corresponds to all available data (including the bursts of 23rd cycle). It is obvious that distribution has kept an asymmetry, and the majority of bursts are observed within 1-2 hours after a 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 Figure 3. 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 similar asymmetry. Hence, it is mainly due to orientation of the sensitivity diagram of the BUST in these directions during GLE events. Exception is an interval 0° – 60° to the West from the Sun-Earth direction. Number of events in this interval differs appreciably from a background event number. The interval between 0° – 60°W contains more than third of all bursts, including three out of four most significant ones.

4. Conclusions

Considerable growth of statistics has given 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 registered bursts and theoretically expected ones. The majority of muon bursts are observed within 1-2 hours after a maximum of X-ray flare. The interval 0° – 60°W is remarkable for large number of bursts in the distribution over ecliptic longitude. As to other intervals there is no essential difference from the background distribution. As mentioned above, observational characteristics of four most significant bursts are similar; in particular, they have the same spatial and temporal properties. Physical interpretation of the obtained results is rather difficult task and should be a subject of separate study.

5. Acknowledgements

Work is supported by the Russian Foundation of Basic Research (projects 04-02-16952, 02-02-16199, 03-02-96026) and by the State Program of Support of Leading Scientific Schools (grants SS-1445.2003.2, SS-1828.2003.02).

References

[1] D.V. Reames, Space Science Rev. 90, 413 (1999).
[2] L.I. Miroshnichenko, Solar Cosmic Rays, Dordrecht: Kluwer Academic Publishers (2001).
[3] L.I. Miroshnichenko, Izv. RAN, Ser. Phys. 67, 462 (2003).
[4] M.A. Shea and D.F. Smart, 27th ICRC, Hamburg (2001) SH1.07, 3401.
[5] S.N. Karpov, L.I. Miroshnichenko, E.V. Vashenyuk, Izv. RAN, Ser. Phys. 61, 1466 (1997).
[6] S.N. Karpov, L.I. Miroshnichenko, E.V. Vashenyuk, Nuovo Cim. 21C, 551 (1998).
[7] S.N. Karpov et al., 28th ICRC, Tsukuba (2003) SH1.4, 3407.