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Study of the GLE events with use of the EAS-arrays data

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Analysis of the Ground Level Enhancements (GLE) occurred in the current 23rd cycle of solar activity was made with using the data of three Baksan detectors: Andyrchy, Carpet and BMD. The GLE events, which have been observed in the 21-22 cycles, are also analyzed by the Carpet data only. The intensity increases related to Solar Cosmic Rays (SCR) have been registered in 15 cases from 30 GLE events studied. It indicates that the increases caused by SCR with energy above 5 GeV were observed nearly in 50% of specified events. The intensities of SCR with such energy differ in various GLE events much less than the intensities at the energy of few GeV. Almost all found increases make up the tenth shares of percent. Therefore, they cannot be registered on neutron monitors with a similar geomagnetic cutoff.

1. Introduction

The worldwide network of neutron monitors (NMs) allows determining a spectrum of solar cosmic rays (SCR) in the majority of GLE events only up to energy 4-5 GeV. Exceptions are only huge events such as 23 February 1956, 29 September 1989 and some others. Instruments with large geometric factor and with high efficiency are necessary for measuring a high-energy part of the SCR spectrum because excess above a background in this area is rather small. Therefore, in addition to the NM data, we suggest to use the information of existing detectors used for registration of various components of extensive air showers (EAS). Namely, for determination of the SCR spectrum at energies exceeding 5 GeV we suggest using the counting rate of single particles at the EAS-arrays and at the muon detectors with large sensitive area. The minimal energy for the one-particle mode of registration of such detectors, as a rule, is determined also by a geomagnetic cutoff, as for NMs. But counting rate of such detectors is several orders of magnitude higher than that for NMs. As known, typical statistical accuracy of NMs makes up 1.0–0.5 % by the 5-minute data. On the contrary, two Baksan EAS-arrays (Andyrchy and Carpet) and Baksan Muon Detector (BMD) under the same conditions have accuracy of 0.055 %, 0.03 % and 0.04 %, respectively. As a result, it allows measuring ten times weaker cosmic ray flux.

The first reliable registration of SCR at the EAS-array was carried out by the Baksan detector Carpet [1]. During GLE event of 29 September 1989 the Carpet has registered huge increase with amplitude (43.30±0.03) % in counting rate of the single particles. And it is more important that the increase with amplitude (14.0±0.5) % was also registered in counting rate of the local showers of low power. The fact of such registration stimulated the searches for SCR effects by large non-standard detectors (BUST [2, 3], MILAGRITO [4], L3+C [5] and GRAND [6]).

2. Detectors and method of the analysis

All three detectors (Andyrchy, Carpet and BMD) are in Baksan valley on North Caucasus (geographical coordinates 43.28°N, 42.69°E). The geomagnetic cutoff rigidity is equal 5.7 GV (according to Tsyganenko-1989 model). The height above sea level makes up 1700 m for the Carpet and BMD and 2050 m for the Andyrchy. All detectors consist of flat scintillation counters with total squares 196, 175 and 37 m^2, respectively. The counting rate of both EAS-arrays is composed of hard component (high-energy muons and hadrons; ≈55 % of counts for the Andyrchy and ≈70 % for the Carpet) and soft component (low-energy muons, hadrons and electromagnetic component, ≈45 % and ≈30 % of counts, accordingly). The BMD is at the depth of 6 m.w.e. and registers muons with energy ≥1.2 GeV that corresponds to the minimal energy losses in the ground.

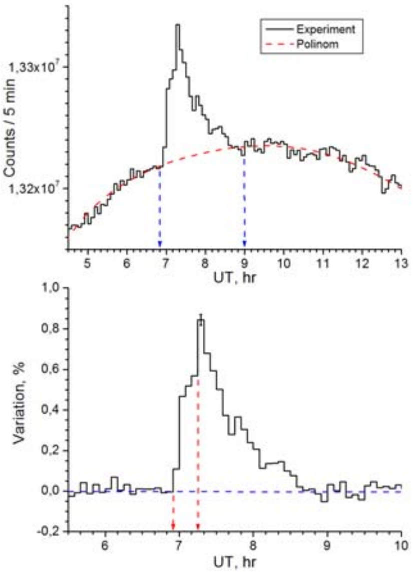

Figure 1. The GLE event of 20 January 2005 by the data of the Baksan Carpet. Top panel – real counting rate of the Carpet and polynomial approximation of the background. Bottom panel – deviation of counting rate from the polinom.

The 5-minute data of registration of single particles on each detector were used in the analysis. The standard correction of data on barometric effect was carried out before the beginning of analysis. The barometric coefficient is equal to –0.38 %/mbar for the Andyrchy and Carpet and is equal to –0.16 %/mbar for the BMD. The data on a temperature profile for the atmosphere above the registration point are absent. In this case the right correction of temperature effect for muons is impossible. Therefore, the corresponding correction of data was not made.

The excess in percentage above a background of Galactic Cosmic Rays (GCR) and also the time profiles of relative intensity were used at studying of the SCR increases. According to the standard technique [7] applied to the NMs data, the average counting rate during 1 hour previous to the onset of flare is accepted usually as the background level. In other words, linear extrapolation (constant) of the background level before the flare is used over total duration of GLE event. For EAS-arrays such approach seems to be unsuitable. Their accuracy is ten times higher than at NMs. The variations with value ≤1% are not visible at NMs over the 5-minute data. But at EAS-arrays they are statistically significant and comparable in size with expected effect from SCR. Even after correction of atmospheric effects the specified variations are not completely eliminated. Therefore, we used the following procedure of a flattening of background.

The data of the counting rate of each Baksan detector within several hours prior to the beginning of GLE and some hours after were approximated by a polynomial function. At the same time, the data registered during GLE were excluded from approximation irrespective of presence of intensity increase. Resultant polynomial dependence gives average value of the background. Then the deviation of real counts of detectors from the polynomial function in percentage was calculated for each moment of time. Thus, all variations (including the temperature effect) are practically excluded, excepting for the SCR increase if it took place. Figure 1 illustrates meaning and result of application of procedure «flattening of background» on the example of GLE event occurred on 20 January 2005. The GLE events of 23rd cycle have been analyzed earlier [8, 9] without using of the «flattening of background» procedure. Only amendments of atmospheric effects were made. The comparison of old and new results shows that the «flattening of background» technique provides more exact estimation of size of the SCR increase than extrapolation of the background by a constant.

3. Main results

Analysis of GLE events of the current 23rd cycle of solar activity was made by above method with using data of three Baksan detectors: Andyrchy, Carpet and BMD. The GLE events occurred at 21-22 cycles were also analyzed by the Carpet data only. In total 30 GLE events have been analyzed. The results obtained over 5-minute data of three Baksan detectors are summarized in Table 1 only for those GLE events when excess above background more than 4 standard deviations was observed at least at one of Baksan detectors. The time moments of onset and maximum of increase and also the excess above the GCR background in percentage and in standard deviations are given for the maximum of each increase. The increases exceeding 4 standard deviations are found in 15 cases from 30 GLE events studied.

Table 1. The Ground Level Enhancements (GLE) by the 5-minute data of the Carpet, Andyrchy and BMD

No.	Date		Carpet		*		Andyrchy		**		BMD		***
GLE		Start	Max.	Inc.%	σ	Start	Max.	Inc.%	σ	Start	Max.	Inc.%	σ
36	811012	0736	0822	0.26	8.7								
38	821207	2356	2410	0.28	9.3								
39	840216	0856	0910	0.14	4.7								
42	890929	1148	1212	43.30	1443								
45	891024	1816	1834	0.48	16								
48	900524	2056	2114	0.36	12								
49	900526	2128	2214	0.76	25								
52	910615	0850	0920	0.66	4.1								
55	971106	—	—	—		1205	1235	0.27	5.0				
56	980502	1330	1350	0.43	14	1335	1400	0.40	7.4				
60	010415	1355	1420	0.47	16	1350	1415	0.59	10	1355	1550	0.18	4.4
61	010418	0215	0320	0.58	19	0220	0315	0.60	11	0215	0300	0.35	8.2
65	031028	1105	1145	0.66	22	1115	1140	0.81	15	1100	1145	0.21	5.2
66	031029	2140	2150	0.56	19	2140	2155	0.50	8.7	2140	2150	0.29	7.2
69	050120	0655	0715	0.85	28	—	—	—		0655	0710	0.25	6.2

* Base statistical accuracy of the Carpet is 0.03% by 5-min data. During GLE52 accuracy of the Carpet is 0.16%.
** The Andyrchy is operating since 1996. Base accuracy of the Andyrchy is 0.055% by 5-minute data.
*** The BMD data is available since 2000. Base accuracy of the BMD is 0.04% by 5-minute data.
σ – Magnitude of the GLE increase in standard deviation at the Baksan detectors

Comparison of the results of Table 1 with the data of NMs shows that the SCR intensity in energy range >5 GeV differs for various GLE events much less than in the range ≤1 GeV. So, the amplitudes of increases at the NMs vary from several percent up to several hundreds and even up to several thousands percent, i.e., over three orders of magnitude. Data of Baksan detectors lay within one order of magnitude: from 0.14 % up to 0.85 %. Exception is only huge increase of 29 September 1989 that most likely is due to unique conditions of observation for the Carpet in this event. Thus, the spectrum of SCR at high energy is more permanent for various GLE events.

All increases under discussion make up the tenth shares of percent (excepting for 29 September 1989), so they could not be registered by neutron monitors with a similar geomagnetic cutoff rigidity. Thus, the data of the Andyrchy, Carpet and BMD allow prolonging spectrum of SCR in the specified events, at least, up to 5-7 GeV. Spectra of SCR for some GLE events were obtained elsewhere [10, 11] using data of three Baksan detectors. The response functions and specific yield functions for the Andyrchy, Carpet and BMD have been also calculated [12], so that the data of Baksan detectors could be used in the analysis of SCR spectra by a uniform technique with the NMs data.

Two spectra for GLE of 20 January 2005 near to a maximum of increase at stations of northern hemisphere (07:15 UT) are depicted in Figure 2. The spectra have been calculated in two versions – with and without using of the Carpet data. As one can see, the addition of the Carpet data almost does not affect a behavior of the spectrum in the energy range up to several GeV. At higher energy the difference reaches already several orders of magnitude. It may be explained by the fact that in the energy range above 3-4 GeV there are practically no reliable data of NMs (the signal is comparable with fluctuations), and the spectrum represents free extrapolation from lower energy. The precise data of the Carpet (0.85 % = 28 standard deviations) fix intensity near energy of 5-7 GeV, where sensitivity of the Carpet is the best. As a result, the exponential spectrum becomes a power-law one, i.e. even the spectrum shape varies. The BMD data are of special interest for determining of SCR spectra as the range of the best sensitivity of this detector is near 7-9 GeV.

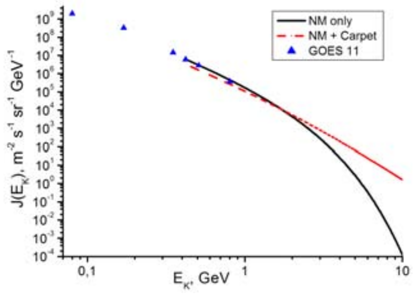

Figure 2. Two spectra for GLE of 20 January 2005 in 07:15 UT, which have been calculated in two versions – with and without using of the Carpet data.

4. Conclusions

Three Baksan detectors (Andyrchy, Carpet and BMD) have registered 15 increases of SCR from 30 GLE events under investigation. It means that SCR with rigidity above 5.7 GV were observed not less than in 50 % of GLE events. The amplitude of a signal in all cases (excepting for 29 September 1989) makes up the tenth shares of percent. Such increases cannot be found on standard neutron monitors with a similar geomagnetic cutoff rigidity. Only high statistical accuracy of Baksan detectors allows registering significant increases of SCR of such rigidity. Due to this there is an opportunity to prolong spectrum of SCR in the specified events above 5 GeV. Thus, the data of Baksan detectors with high accuracy fix spectrum of SCR in the energy range where the data of the NMs network, as a rule, are absent or are insufficiently reliable. The carried out analysis shows that intensity of SCR with energy >5 GeV varies from one GLE to another much less than in the range of several GeV.

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