

Estimation of SCR spectrum in the GLE#70 event based on the data of muon hodoscopes of Experimental complex NEVOD

Elena Yakovleva, Anna Dmitrieva, Viktor Shutenko and Dmitry Timashkov

Moscow Engineering Physics Institute (State University), Moscow 115409, Russia

Abstract. Preliminary estimates of solar cosmic ray spectrum for the event of December 13, 2006 (GLE#70) which has been detected by several supermodules of the muon hodoscope located in the experimental complex NEVOD (MEPhI) have been obtained. Comparison of the solar cosmic ray spectrum parameters in this event with results of others works is discussed. It is shown that for solar cosmic rays, which have usually a soft spectrum, the effective proton energies lie near the lower boundary of the detector sensitivity range.

Keywords: GLE#70 event, solar cosmic rays, muon hodoscope

I. INTRODUCTION

The study of high-energy particles from the Sun gives possibility to investigate conditions of their generation in solar flares and also to explore the impact of solar cosmic rays (CR) on processes in the interplanetary space, magnetosphere, ionosphere and the Earth's atmosphere. Relativistic solar protons are observed in the relatively rare events after powerful solar flares, and the use of ground-based detectors of cosmic rays are the basic method of their registration (neutron monitors, muon telescopes and muon hodoscopes). The last similar event was the powerful flare on December 13, 2006. The estimations of the spectrum of this event were obtained earlier with the analysis of data of neutron monitors, which allow one to study variations of the cosmic rays in the range of energies of several GeV [1-6]. The new possibilities of the ground-based monitoring of CR variations are opened with the use of muon hodoscopes, which make it possible to directly observe space-angular variations of cosmic ray muons during GLE event [7] and give the possibility to investigate solar cosmic rays in the range of energies up to several tens GeV.

This work is devoted to the analysis of the characteristics of solar CR spectrum in the GLE#70 event according to the data of several supermodules of muon hodoscope which is under operation in the experimental complex NEVOD (MEPhI) [8]. Muon hodoscope consists of separate supermodules with area 11.5 m² each, located above the NEVOD water tank. Total threshold energies vary from 200 MeV to 600 MeV depending on zenith angle. The track parameters of each muon are determined in the real time regime with angular accuracy of 0.7°. The detailed description of muon hodoscope URAGAN can be found in [9].

II. METHOD OF DETERMINATION OF SOLAR CR SPECTRUM

The characteristics of spectra of primary CR can be obtained by the solution of inverse problem by means of coupling functions for the muon hodoscope, which join the differential muon flux at the Earth's surface and the proton flux above the atmosphere [10-11]. Increase of detector counting rate can be written through coupling functions as follows:

$$\delta_{\text{model}} = \int P(E, \theta_i, \varphi_j) \cdot J_p^{\text{SCR}}(E) dE \text{ [counts/s]} \quad (1)$$

where E is proton energy, $J_p^{\text{SCR}}(E)$ – spectrum of solar CR, $P(E, \theta_i, \varphi_j)$ – yield function of the detector. Since usually the experimental value of increase in counting rate δ_{exper} is given in percent, it is convenient to use yield function $P_1(E, \theta_i, \varphi_j)$ which is normalized to detector counting rate in quiet conditions n^{GCR} (from galactic CR $J_p^{\text{GCR}}(E) = 1.8 \cdot E^{-2.7} \text{ [cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}]$, see [12]).

$$P_1(E, \theta_i, \varphi_j) = \frac{P(E, \theta_i, \varphi_j)}{n^{\text{GCR}}} \cdot 100\% = \frac{P(E, \theta_i, \varphi_j)}{\int P(E, \theta_i, \varphi_j) \cdot J_p^{\text{GCR}}(E) dE} \cdot 100\% \quad (2)$$

In Fig. 1, the yield functions P_1 for eight zenith angle intervals of the muon hodoscope and for Moscow neutron monitor (MNM) are shown.

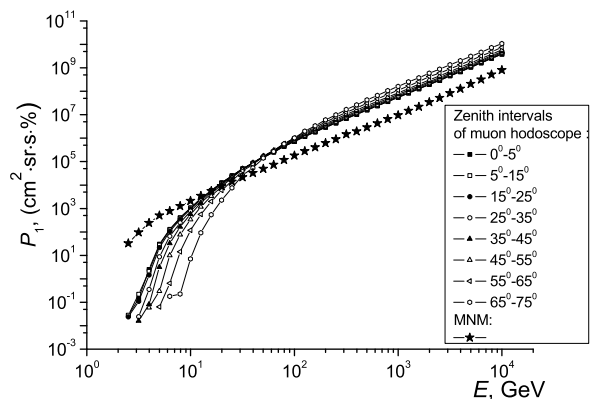


Fig. 1: Yield functions P_1 for three supermodules of muon hodoscope and for Moscow neutron monitor.

Using functions P_1 one can join solar CR spectrum and the increase of detector counting rate (in percent):

$$\delta_{1\text{model}} = \int P_1(E, \theta_i, \varphi_j) \cdot J_p^{\text{SCR}}(E) dE \quad [\%] \quad (3)$$

If the spectrum of solar CR is assumed in the form:

$$J_p^{\text{SCR}}(E) = J_0 \cdot E^{-\gamma} \text{ [cm}^2\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}\text{]}, \quad (4)$$

where E is substituted in GeV, then for determining the parameters of the spectrum (J_0 and γ) it is necessary to minimize the function:

$$F(J_0, \gamma) = \sum_M \left(\frac{\delta_{1\text{model}}^{(M)} - \delta_{\text{exper}}^{(M)}}{\sigma_M} \right)^2 = \sum_M \left(\frac{\int P_1^{(M)}(E, \theta_i, \varphi_j) J_0 E^{-\gamma} dE - \delta_{\text{exper}}^{(M)}}{\sigma_M} \right)^2 \quad (5)$$

where $\delta_{\text{exper}}^{(M)}$ is the measured increase of counting rate (in percent) in the M -th detector; σ_M – errors of experimental values. A specific feature of muon hodoscope data analysis consists in that its zenith-angular intervals can be considered as separate detectors with different yield functions, since the data in each angular interval are independent of each other.

III. RESULTS

The analysis of GLE#70 event was carried out using 5-min data of muon hodoscope and Moscow neutron monitor [13] by means of two methods. In the first case, data of the zenith intervals of muon hodoscope supermodules were only used, in the second one the data of muon hodoscope together with MNM were analyzed. In Fig. 2, variations of counting rates for five zenith angle intervals of muon hodoscope and also of MNM are shown. As the zero level, the average value of detector counting rate over the time period from 00:00 to 02:30, December 13, 2006 is selected.

In Table I, the experimental points for five zenith intervals of muon hodoscope and MNM for the time 3:00 UT are listed.

TABLE I: The excess of CR flux in muon hodoscope and MNM data (at 3:00 UT).

Detector	Angular bin	Increase of counting rate
URAGAN	0°-5°	2.53 ± 0.69 %
	5°-15°	1.18 ± 0.37 %
	15°-25°	0.98 ± 0.28 %
	25°-35°	1.00 ± 0.26 %
	35°-45°	0.48 ± 0.26 %
MNM	–	23.14 ± 0.53 %

In Fig. 3, the dependences of functions (5) on the parameter γ are presented. Functions are calculated for two cases described above (see Fig. 3a and 3b). The parameters J_0 and γ of solar CR spectrum for these two cases are presented in Table II. Evidently, the addition of neutron monitor data (Fig. 3b) to the function (5) results in a more sharp minimum.

TABLE II: Estimated parameters of solar CR spectrum for GLE#70 event (at 3:00 UT).

	γ	J_0 , (cm ² s sr GeV) ⁻¹	F/d.o.f.
Data of muon hodoscope	5.5 ± 2.8	≈ 65	1.04
Data of muon hodoscope and MNM	5.06 ± 0.33	≈ 21	0.80

The parameter γ of solar CR spectrum obtained above is in a good agreement with other works in which the data of neutron monitors are used. For example, in work [1] the following spectrum: $J_p(R) = 17 \cdot R^{-(4.25+0.11(R-1))}$ is given, where R is the rigidity of primary particles. In the later work [2] of the same authors the spectrum was presented as: $J_p(E) = 48 \cdot E^{-(4.73+0.14(R-1))}$. Since typical primary energies for the muon hodoscope lie in the range 5-15 GeV, index γ of power-law spectrum is in the range from 4.7 to 5.8 for [1] and from 5.3 to 6.7 for [2], that is close to results of our analysis. In both cases, J_0 coincides by the order of magnitude with the values obtained from muon hodoscope data. A good agreement is observed in comparison with the work [3], in which γ is estimated as 5.5 ± 0.5 , the same value of γ is given in the works [4] and [5]. However, in work [6] the estimate of γ composes 6.36, that is larger than found in other works. As a whole, the comparison shows that the slope of the spectrum does not seriously change at high energies. With the use of the obtained spectrum it is possible to estimate energies of solar protons, response for which is registered by muon hodoscope and neutron monitor. Considering the function

$$G(E, \theta_i, \varphi_j) = P(E, \theta_i, \varphi_j) \cdot J_p(E), \quad (6)$$

as the distribution of detector response in primary CR energy, it is possible to determine the average energy E_{av} of primary protons which give main contribution to counting rate of the detector and upper boundary of energies of the primary protons $E_{0.95}$, above which the contribution to counting rate of the detector comprises 5%. The values of these energies are given in Table III.

TABLE III: Average and maximum energies of primary protons for GLE#70 event.

Detector	Angular bin	Average energies E_{av}	Maximum energies $E_{0.95}$
URAGAN	0°-5°	9.3	23.7
	5°-15°	9.4	24.4
	15°-25°	9.8	25.3
	25°-35°	11.3	29.3
	35°-45°	12.8	33.2
MNM	–	3.7	7.1

It is obvious that the mean energy for the neutron monitor is almost 3 times lower than that for the muon hodoscope. Thus, muon hodoscope really extends the range of energies for study of solar CR to tens GeV region, which is inaccessible for the neutron monitors.

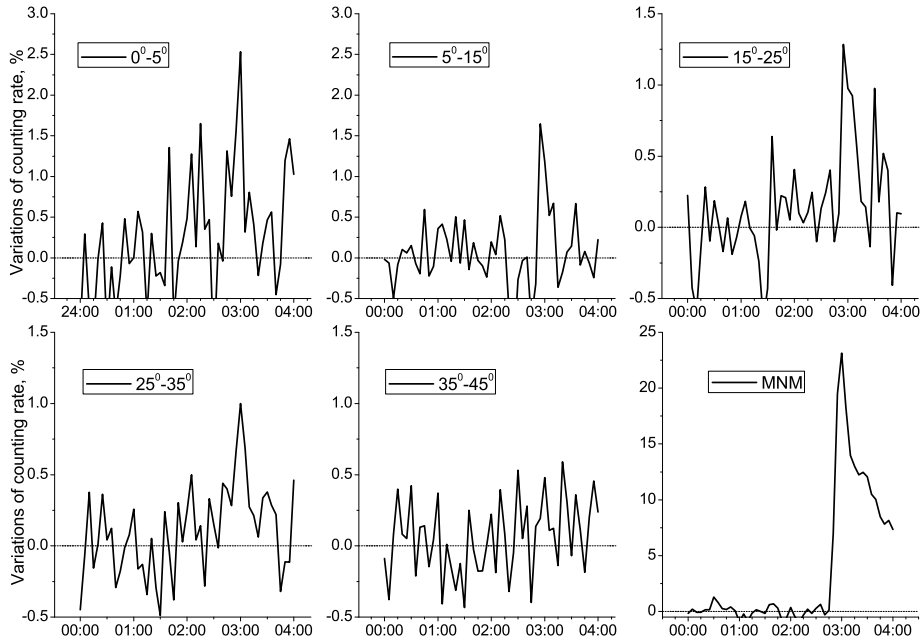


Fig. 2: Variations of counting rates before and during GLE#70 event for five zenith-angular intervals of muon hodoscope and MNM.

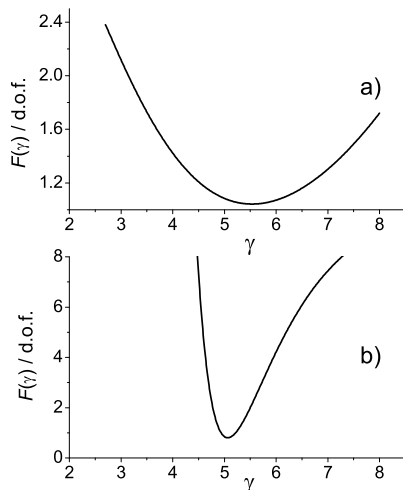


Fig. 3: Functions (5): a) using only muon hodoscope data, b) using muon hodoscope and Moscow neutron monitor data.

On the other hand, for solar CR spectrum in this event (and in many other GLE events with nearly the same γ value), maximum energies of primary protons giving the main contribution to the muon hodoscope counting rate do not exceed 30 GeV.

IV. CONCLUSION

Estimates of solar CR spectrum in the GLE#70 event (December 13, 2006) which was registered by several supermodules of muon hodoscope URAGAN are obtained. In the analysis, the data of muon hodoscope in several zenith-angular intervals and also data of Moscow neutron monitor were used.

Two versions of solar CR spectrum estimates in this event are obtained: 1) according to only muon hodoscope data : $J_p(E) = 65 \cdot E^{-5.5 \pm 2.8} [\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}]$, 2) according to muon hodoscope data and data of Moscow neutron monitor: $J_p(E) = 21 \cdot E^{-5.06 \pm 0.33} [\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}]$.

The parameters of the spectrum in GLE#70 event estimated in this analysis are in a good agreement with the values found in other works. Average and maximum energies of solar protons are calculated. It is shown that effective energies for the muon hodoscope are about 3 times higher than those for the neutron monitor. However, even for the muon hodoscope maximum energies of solar protons do not exceed 30 GeV.

V. ACKNOWLEDGMENTS

The research is performed in Scientific and Educational Centre NEVOD with the support of the Federal Agency for Science and Innovations (contract 02.515.11.5077) and RFBR (grant 06-02-17213-a).

REFERENCES

- [1] E.V. Vashenyuk et al. // Proc. 30th ICRC, Merida, 1 (2007) 221.
- [2] E.V. Vashenyuk et al. // Geomagnetism and Aeronomy, 48, No. 2 (2008) 149.
- [3] V.G. Grigoryev et al. // Advances in Space Research, 43 (2009) 515.
- [4] E.V. Vashenyuk et al. // Proc. 30th ICRC, Merida, 1 (2007) 253.
- [5] P. Stoker // Proc. 30th ICRC, Merida, 1 (2007) 201.
- [6] E.O. Fluckiger et al. // Proc. 30th ICRC, Merida, 1 (2007) 289.
- [7] D.A. Timashkov et al. // Astroparticle Physics, 30 (2008) 117.
- [8] NEVOD Laboratory, <http://www.nevod.mephi.ru>
- [9] N.S.Barbashina et al. // Instr. Experim. Tech., 51 (2008) 180.
- [10] E.I. Yakovleva et al. // Bull. Rus. Acad. Sci. Phys., 73 (2009) 357.
- [11] A.G. Bogdanov et al. // Proc. 21st ECRS, Kosice, 2008. S4.05.
- [12] S. Eidelman et al. // Physics Letters B 592, 1 (2004).
- [13] Moscow Neutron Monitor. <http://cr0.izmiran.rssi.ru/mosc/main.htm>