The features of the study of Forbush effects in the flux of muons

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***Abstract*—Muon rate variations during Forbush decreases registered by means of muon detectors DECOR and URAGAN operated in the experimental complex NEVOD (MEPhI, Moscow) are studied. Analysis of the data of these setups has been performed using a technique that allows to reduce both statistical and systematic uncertainties. Preliminary results on dependences of Forbush decrease amplitude on effective primary proton energy have been presented. "Muon images" of Forbush decrease obtained by means of the unique muon hodoscope URAGAN, which gives a possibility to observe angular dynamics of muon flux anisotropy, are also shown.**

1. Introduction

THE disturbances of the interplanetary magnetic field, caused by solar activity, often lead to a sharp decrease of the flux of primary cosmic rays in the heliosphere. This phenomenon, called Forbush decrease (FD), for the first time was observed in the registration of charged cosmic ray particle flux (mainly muons) at the Earth's surface. However, its further studies for a long time were usually conducted with neutron monitors. The relatively low energy of primary cosmic rays to which neutron monitors are sensitive, and as a consequence considerable amplitudes of the effect are advantages of this approach. Last forty years, monitoring of Forbush decreases is performed by means of the world-wide network of neutron monitors. However to explore modulations of galactic cosmic rays with energies of tens GeV during Forbush effects the possibilities of neutron monitors are somewhat limited. Besides, the absence of information about the direction of the arrival of cosmic ray particles is another significant drawback of neutron monitors.

The appearance of multidirectional muon telescopes and later of muon hodoscopes revealed new possibilities in studies of Forbush decreases [1]. The important advantage of muon hodoscope is a possibility to simultaneously register muons from different directions and to form "muon images" of the sky hemisphere. On the other hand, the reduction of the amplitude of FD with the increase of energy imposes higher demands to the accuracy of the determination of the basic parameters of FD.

In this work, the analysis of the Forbush decreases registered in muon detectors DECOR [2] and URAGAN [3] in 2004 – 2006 is conducted.

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2. Detectors and experimental data

The coordinate detector DECOR was deployed around the Cherenkov calorimeter NEVOD [4]. The side part of DECOR includes eight 8-layer supermodules (SM), 8.4 m^2 area each, with vertical planes of streamer tube chambers. Top supermodules of DECOR are located on the cover of the calorimeter water tank and are assembled of eight horizontal streamer tube chamber layers interlaid with 10 cm foam plastic. For the present analysis, coincidences between signals from any side DECOR supermodule and any top DECOR SM are used. Such condition provides registration of muons with energy $E > 2$ GeV.

In 2005, on the basis of top DECOR supermodules a new multipurpose muon hodoscope URAGAN was constructed. The URAGAN supermodule includes eight planes interlaid with 5 cm foam plastic, each composed of 320 streamer tubes (1 cm $\times$ 1 cm $\times$ 350 cm) with external strips (along and across streamer tubes) forming two-dimensional readout system (608 data channels in each plane). Total area of one supermodule is about 11.5 m^2. The setup provides detection of particles in a wide range of zenith angles (from 0 to 80°) with angular accuracy about 0.7°. The data processing system allows to reconstruct muon tracks in on-line mode and to register muon flux from the upper hemisphere as continuous sequence of 2D-pictures. Threshold energies of the URAGAN depend on zenith angle and lie within limits from 200 MeV to 600 MeV.

In the present work, ten FD detected by means of these setups in 2004 – 2006 are considered. In the analysis, 10 min non-normalized data corrected for barometric effect are used. Median energies of primary particles giving main contribution to muon detector counting rate are calculated on the basis of CORSIKA simulation using methods described in [5].

To exclude the influence of atmospheric effects on muon flux intensity at ground level, the technique of eliminating of various trends and background variations has been developed. This approach reduces the uncertainties in the estimation of the amplitude of Forbush decrease.

3. Method of FD parameter determination

Analysis of Forbush effect begins from the choice of the moments of start and stop of counting rate decrease: t_1 and t_2 (Fig.1) and selection of time series before t_1 (I_b) and after t_2 (I_r). Using linear fits of the series $I_b(t)$, the biases $B_b^{(i)}$ during i days (i = 1, 2, 3) are calculated, and compensated time series $I_{bs}^{(i)}(t)$ are formed: $I_{bs}^{(i)}(t) = I_b(t) - B_b^i \times (t - t_1)$.

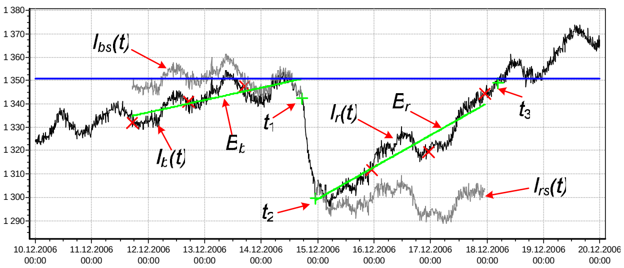

Figure 1. Parameters which characterize Forbush decrease.

After that, the series $I_{bs}^{(i)}(t)$ are averaged over j days ($j \le i$) and mean values of counting rate before Forbush effect $\langle I_{bs}^{(i,j)} \rangle$ are obtained. Similarly, the mean values of counting rate after Forbush decrease $\langle I_{rs}^{(k,m)} \rangle$ are calculated, where k = 1, 2, 3 days is time interval for biases calculations, $m \le k$ is an interval for averaging. Thus, considering various variants of mean counting rate values before and after FD, the set of 36 relative amplitude values may be calculated:

$$A_{ij}^{km} = \left(\left\langle I_{bs}^{i,j} \right\rangle - \left\langle I_{rs}^{k,m} \right\rangle \right) / \left\langle I_{bs}^{i,j} \right\rangle \times 100\% . \quad (1)$$

Average value of obtained relative amplitudes A_{ij}^{km} is assumed as Forbush decrease amplitude A_{FD}, and the value of rms-deviation of A_{ij}^{km} is used as estimation of A_{FD} error. By means of this method, variations of cosmic ray flux measured with muon hodoscopes DECOR and URAGAN were analyzed. Data of Moscow neutron monitor were also considered.

3. Dependence of decrease amplitude on median energy

During the period 2004–2007, muon detectors DECOR and URAGAN detected ten Forbush decreases. Using procedure described above, the basic parameters which characterize FD, including the amplitude A_{FD} in the integral counting rate, were determined (see Table 1). For the comparison, the data of Moscow neutron monitor (IZMIRAN) were also analyzed.

Muon hodoscope URAGAN detected eight FD, and for each of them the values of amplitudes for five zenith-angular intervals (0°–17°, 17°–26°, 26°–34°, 34°–44° and more 44°) were determined. Median energies of primary protons ($E_{0.5}$) which give the contribution to counting rate of the muon hodoscope in these zenith intervals were also calculated and their values are equal to: 13.4 GeV, 14.3 GeV, 16.2 GeV, 18.3 GeV and 24.1 GeV, respectively.

Table 1. Characteristics of analyzed FD.

Date of FD	K_p-index	A_{FD}, %		
		Moscow NM	URAGAN	DECOR
22 Jan 2004	7	7.07 ± 0.40	-	2.43 ± 0.19
8 May 2005	7	4.82 ± 0.51	2.71 ± 0.13	1.74 ± 0.07
15 May 2005	9	7.13 ± 0.17	2.52 ± 0.17	2.07 ± 0.09
29 May 2005	6	3.77 ± 0.13	-	1.57 ± 0.26
20 Feb 2006	6	1.29 ± 0.09	0.30 ± 0.06	-
13 Apr 2006	4	1.27 ± 0.14	1.22 ± 0.05	-
9 Nov 2006	4	1.63 ± 0.11	0.87 ± 0.02	-
14 Nov 2006	2	1.33 ± 0.08	0.65 ± 0.05	-
29 Nov 2006	3	1.79 ± 0.10	1.04 ± 0.17	-
14 Dec 2006	8	-	3.78 ± 0.12	-

Capabilities of muon hodoscope allow reconstruct dependence of FD amplitude on primary proton energy using data even from a single detector for different zenith angle bands. We fit this dependence using a power-like function in a following form

$$A_{FD} \sim \left(E_{0.5}^{FD} \right)^{-\alpha} . \quad (2)$$

According to the value of the parameter α, the events can be separated into “soft” (with exponent about 1) and “hard” (exponent value less than 0.5). Soft dependence of amplitude on primary energy may be caused by the fact that primary CR modulations touch very wide energy range and top boundary of energy interval of CR modulation is significantly higher than characteristic primary energies in this direction. In two events, the fitting demands to use two different values of α. In the cases when the upper boundary of energy interval of CR modulation lies within muon detector sensitivity range, a typical threshold behavior of $A_{FD}\left(E_{0.5}^{FD}\right)$ is observed.

In Fig.2, the dependences of the amplitude of FD on the median energy are presented for three FD, registered on May 15, 2005; December 14 and November 9, 2006. These events illustrate “hard”, “soft” and “threshold” behavior of FD amplitude, respectively.

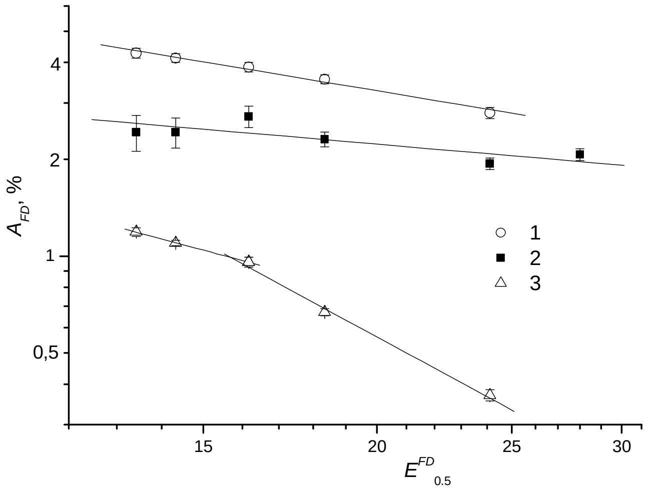

Figure 2. Dependence of FD amplitudes on median energy. 1 – 14 Dec 2006 (α = 0.72 ± 0.08); 2 – 15 May 2005 (α = 0.37 ± 0.11); 3 – 9 Nov 2006 (α_1 = 1.15 ± 0.26 and α_2 = 2.34 ± 0.17).

Comparison of these events with the disturbances of the solar wind and magnetosphere of the Earth shows that corresponding heliospheric perturbations are lined up in the same order (the strongest on May 15, 2005; the most weak on November 9, 2006).

4. Spatial-temporal dynamics of muon flux during FD of November 14, 2006

Main peculiar feature of muon hodoscope URAGAN is the possibility of measurements of the spatial-angular structure of muon flux. Excellent angular resolution allows to detect the decreases of muon flux not only for various zenith angles but even for separate solid-angle cells from different directions of the celestial hemisphere.

On-line reconstruction gives values of both zenith and azimuth angles, or projection zenith angles θ_x, θ_y of muon track (in local coordinate system), on the basis of which the track is put in a corresponding cell of two-dimensional matrix. To study muon flux fluctuations, for every cell of this matrix the average number of muons (estimated during preceding 24 hours and corrected for atmospheric pressure) is subtracted, and results are divided by standard deviations. In Figure 3, the sequence of 2D-matrices averaged over 10-minute intervals is presented. To smooth Poisson fluctuations, a special Fourier filter is used. Thin lines identify North-South and West-East directions. Colors represent excess and deficit of muons from a certain direction.

In different frames of the figure, variations of muon flux intensity detected from various directions with time step 30 min are shown. The circles correspond to zenith angles 30°, 45° and 60°. Statistics of each image is equal to about 5 million tracks. From the figure, the two-dimensional angular picture of the decrease of the muon flux and its evolution during the Forbush decrease are seen.

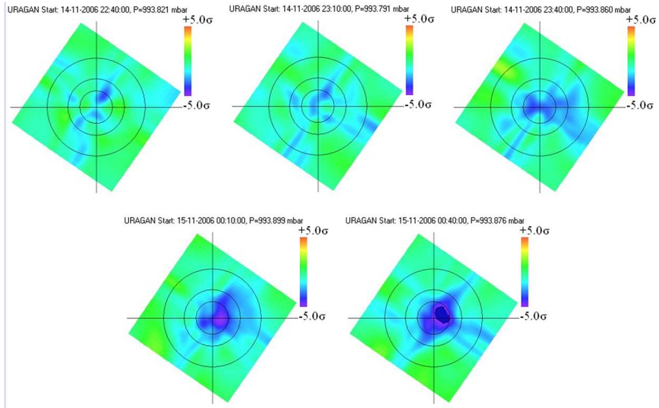

Figure 3. Variations in the muon rate measured by URAGAN in different directions on November 14, 2006 with 30 minute intervals.

4. Conclusion

The analysis of the data of muon detectors of Experimental Complex NEVOD showed that simultaneous measurements of the muon rate in muon detectors with different energy thresholds and at different zenith angles allow investigating the dependence of FD value on the primary energy of galactic cosmic rays.

Detection of muon flux in the hodoscopic mode gives the possibility to obtain unique data on the time-spatial picture of the muon flux from the upper hemisphere during the disturbances of the interplanetary magnetic field and magnetosphere.

Acknowledgment

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