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Investigation of Forbush effects in muon flux measured in integral and hodoscopic modes

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Abstract: Muon rate variations during Forbush decreases registered by means of muon detectors DECOR, TEMP and URAGAN operated in the experimental complex NEVOD (MEPhI, Moscow) have been studied. Analysis of data of these setups has been performed using a special technique that reduces as statistical as systematic uncertainties. Preliminary muon energy and zenith-angular dependences of Forbush decrease amplitude have been obtained (for 2.4 GV cut-off rigidity). Analysis of data from the new unique muon hodoscope URAGAN allows to study the dynamics of muon flux anisotropy during Forbush effect.

Introduction

A sharp decreasing of galactic cosmic ray intensity during magnetic field perturbations and shock waves propagation in the heliosphere (Forbush effect) is one of the interesting phenomena in solar-terrestrial physics. For study of these phenomena, the worldwide net of neutron monitors located at various points of the Earth is used. Unfortunately, a single neutron monitor cannot give information about the directional changes of cosmic ray flux. From this point of view, investigations of muon flux, which contents about 70% of charged cosmic ray particles at sea level, are very interesting and useful. If muon hodoscopes (detectors, which can measure muons from various directions simultaneously with a good angular accuracy) are used for this purpose, it is possible to measure the changes in muon flux at different zenith and azimuth angles and to study spatial-temporal dynamics of these changes [1].

In this paper the results of muon flux variation studies during the strong Forbush decreases are presented. These data were obtained by means of three muon detectors: two muon hodoscopes TEMP [2] and URAGAN [3], and coordinate detector DECOR [4].

Apparatus and experimental data

Experimental complex NEVOD of MEPhI (Moscow, Russia) among other setups has available three muon coordinate detectors – DECOR, TEMP and URAGAN (Figure 1).

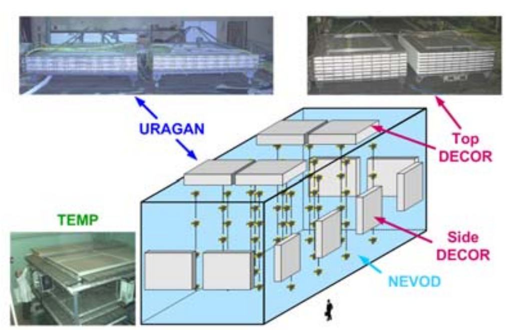

Figure 1: Experimental complex NEVOD.

The first in the world muon hodoscope TEMP consists of two pairs of horizontal coordinate planes (X, Y) with sensitive area of 9 m^2. These pairs are vertically separated by 1 m. Each plane is assembled of narrow scintillator counters (2.5 cm × 1 cm × 300 cm) with PMT. Total number of counters is 512; angular resolution 1 – 2^o. Data are continuously registered as intensity arrays with dimension 255 × 255 directional cells. The coordinate detector DECOR is deployed around the Cherenkov water calorimeter NEVOD [5]. 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 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 (trigger #9) 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 and composed of 320 streamer tubes (1 cm × 1 cm × 350 cm) with external strips (along and across streamer tubes) forming two-dimensional readout system (4864 data channels). Total area of each SM is about 11.5 m^2. The setup provides detection of particles in a wide range of zenith angles (from 0 to 80^o) with angular accuracy about 0.7^o. The data processing system allows to reconstruct muon tracks in the on-line mode and to register muon flux from the upper hemisphere as continuous 2D-pictures. As an example of the Forbush decrease detection with these setups, in Figure 2 variations of the counting rate during 10 - 25 May 2005 from muon detectors and Moscow neutron monitor [6] are presented. Such system of three independent muon detectors operating in one experimental complex gives a unique possibility for the analysis of muon flux variations with various threshold energies.

Integral flux analysis

For the analysis of Forbush decreases (FD), the normalized 10-minute counting rates of three muon detectors of NEVOD complex were used. Corrections for the barometric effect were evaluated and introduced. During the simultaneous operation of muon hodoscopes in 2005 – 2006 several Forbush decreases (FD) were detected.

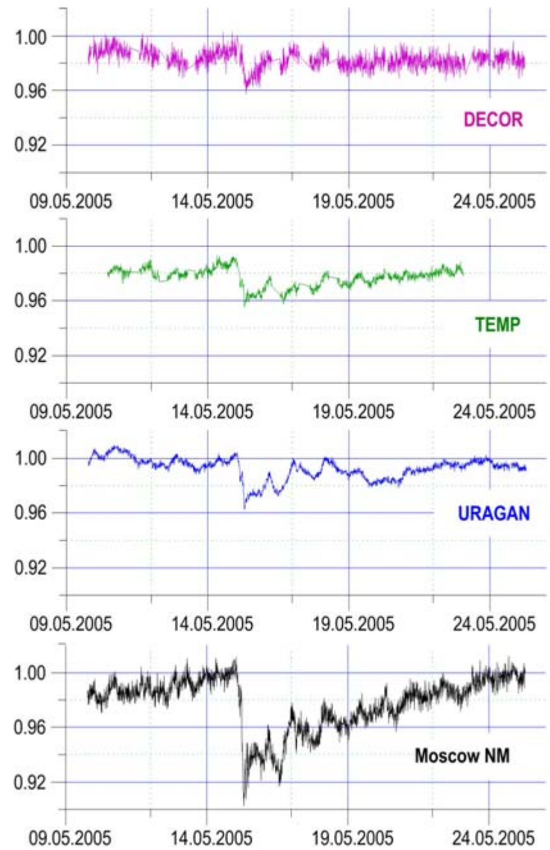

Figure 2: Variations of counting rate in May 2005 from muon detectors DECOR, TEMP and URAGAN and Moscow neutron monitor.

Amplitude of cosmic ray flux decreasing is one of the main Forbush effect parameters. Therefore it is important to measure it correctly and with low uncertainties. The difficulties are related with diurnal cycle and various trends, which modulate cosmic ray intensity behavior. This problem is solved using averaging of muon counting rates before and after Forbush decrease over several intervals (one, two, three days) and determination of FD amplitude as a difference between averaged values. Depending on variants of averaging, several values of FD amplitude were obtained. The difference between them represents the systematic uncertainty connected with changing of diurnal cycles. The amplitude of a given Forbush decrease (A_{FD}) is defined as the average value among a set of different amplitude estimate variants, and its errors are defined as rms deviations over the set. The amplitudes of four FD registered by means of muon hodoscopes of NEVOD complex calculated using this method are presented in Table 1.

Table 1: Amplitudes of decreases in muon rate.

FD	URAGAN, %	TEMP, %	DECOR, %
17 Jan 05	–	5.1 ± 0.29	3.21 ± 0.28
8 May 05	2.17 ± 0.17	–	1.25 ± 0.11
15 May 05	4.00 ± 0.11	–	2.15 ± 0.20
14 Dec 06	3.41 ± 0.13	–	–

To compare muon flux data from different setups, it is convenient to use minimum energy of muons at generation level. This energy consists of muon energy loss during propagation through the atmosphere, energy loss in experimental building, and threshold registration energy of supermodules. Such defined minimum energies are equal to 2.65 GeV for URAGAN, 2.74 GeV for TEMP, and 5.63 GeV for DECOR.

FD at different angles

The important advantage of muon hodoscope is a possibility to register muons from different directions with various zenith angles, which correspond to different minimum muon energies at production. For the analysis, five zenith angle intervals were chosen, proceeding from the same statistical accuracy. In Table 2, values of minimal energies and decrease amplitudes for different zenith angle intervals according to data of muon hodoscope URAGAN during Forbush effect of December 14, 2006 are presented.

In Figure 3, the dependences of FD amplitudes on minimum muon energy for different muon detectors are shown. It is seen from the figure that a single point corresponding to integral URAGAN muon rate during FD of December 14, 2006 turns into five points corresponding to different angular ranges. Thus, with even a single muon hodoscope a broad muon energy interval can be covered.

Table 2: FD amplitudes for various angular ranges.

Zenith angle range	E_{μ}^{min}, GeV	A_{FD}, %
0 – 17°	2.30	3.51 ± 0.16
17 – 26°	2.44	3.53 ± 0.13
26 – 34°	2.63	3.43 ± 0.12
34 – 44°	2.93	3.17 ± 0.11
44 – 80°	3.90	2.69 ± 0.10

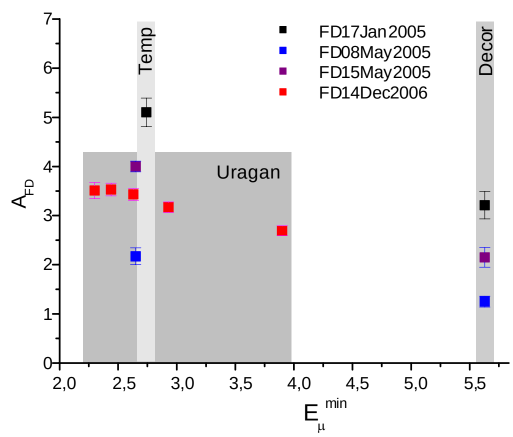

Figure 3: Dependence of FD amplitudes measured by means of TEMP, DECOR and URAGAN on minimum muon energy.

Hodoscopic mode

Another remarkable ability of new muon detector URAGAN is its operation in hodoscopic mode, that is registration of a spatial-angular structure of muon flux. Since 2006, two supermodules of URAGAN are operated. In Figure 4, the preliminary URAGAN data on 2D-dynimics of muon intensity during the Forbush decrease of December 14, 2006 are shown.

On-line reconstruction gives values of both zenith and azimuth angles as projection 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 the angular matrix. For every cell the average number of muons is subtracted and results are divided by standard deviations. To smooth Poisson fluctuations a special Fourier filter is also used. In Figure 4 the sequence of 2D-matrices detected by means of two supermodules during 1-hour exposures is presented. Colors represent excess and deficit of muons from a certain direction. From the figure, a 2D-dynamics of muon flux decreasing and evolution of Forbush effect are seen.

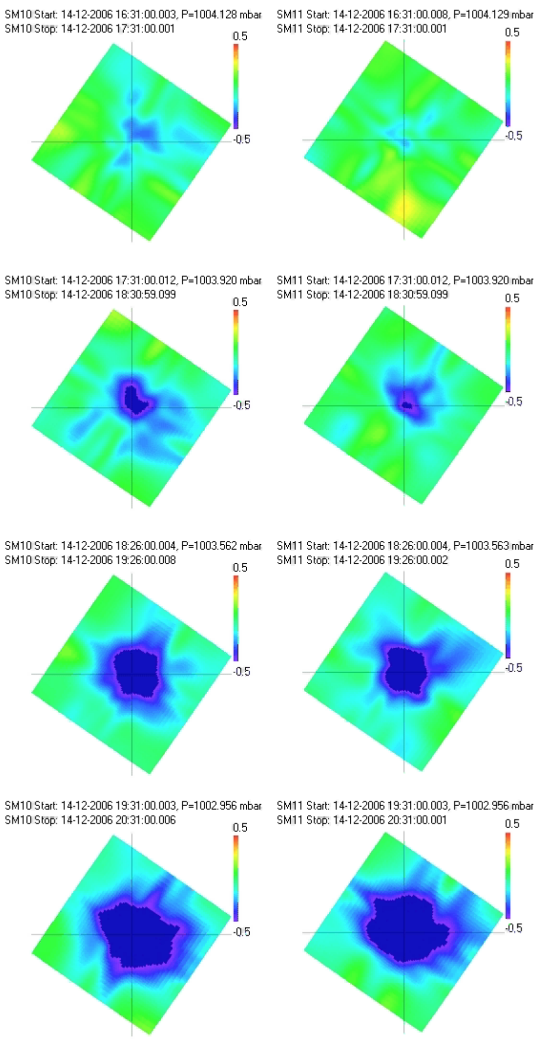

Figure 4: 2D-dynamics of muon flux during Forbush decrease of December 14, 2006.

Conclusion

The system of three independent muon detectors operating in one experimental complex gives a unique possibility to investigate Forbush decreases in high-energy primary particle flux. It is shown that using even a single muon hodoscope a broad zenith angle and muon energy interval can be covered. Analysis of data from the new unique muon hodoscope URAGAN allows to study the dynamics of muon flux anisotropy and to see 2D-dynamics of Forbush effect.

Acknowledgments

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