Study of characteristics of Forbush decreases detected in 2006 – 2011 by means of muon hodoscope URAGAN

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Study of characteristics of Forbush decreases detected in 2006 – 2011 by means of muon hodoscope URAGAN

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Abstract. Results of the study of variations of cosmic ray muon flux at the Earth surface during Forbush decreases (FD) registered in 2006 – 2011 by means of muon hodoscope URAGAN both for the integral counting rate and for different angular intervals are presented. Dependences of the amplitude of the decrease of cosmic ray muon intensity on the energy of primary particles in the energy region above 10 GeV during different phases of the FD were obtained. On the basis of the analysis of spatial-angular distribution of muon flux, values of the horizontal projections of the local anisotropy vector were calculated and their dynamics was studied. Energy, angular and temporal characteristics of Forbush decreases determined from cosmic ray muon data are compared with basic parameters characterizing conditions of near-Earth space before and during FD.

1. Introduction

Construction in 2006 of a wide-aperture precise muon hodoscope [1] which provides continuous registration of muon flux from all directions of the celestial hemisphere has allowed a new level studying of cosmic ray (CR) variations, which are the integral result of various solar, heliospheric, magnetospheric and atmospheric phenomena. Forbush decrease (FD) is one of the bright examples of occasional cosmic ray variations, which represents a sharp decrease of cosmic ray intensity caused by disturbances in the interplanetary magnetic field (IMF) connected with shocks in the solar wind [2]. Forbush decrease investigations were performed with the help of the technique specially developed for the analysis of FD detected in muon flux in the hodoscopic mode.

2. Experimental data and analysed events

Construction and data acquisition system of muon hodoscope URAGAN [1] allow to register nearly continuous zenith-azimuthal dependence of muon flux on the Earth surface with a sufficiently small sampling interval of time. Every minute one supermodule (SM) of muon hodoscope URAGAN registers and writes in a two-dimensional matrix (in the cells of zenith and azimuth angles) information about ~ 80 thousand muons which represent original material for a further analysis. In order to solve different tasks, data of URAGAN can be united both in time and in angular cells, but the original matrix information is conserved. For the analysis of Forbush decreases, data with the size of the cells 1×4 degrees (for zenith-azimuthal grid) are used.
In comparison with earlier studies [3-5], in this article the results of the analysis of muon flux variations during Forbush decreases on the basis of combined data of two (for 2006) or three (for 2007-2011) supermodules with correction for barometric and temperature effects are presented. This combination significantly improved the statistical accuracy of the analyzed time series. Integral counting rate and counting rates for five intervals of zenith angle with a similar statistical accuracy 0°-17°, 17°-26°, 26°-34°, 34°-44° and 44°-80° are used. Threshold energy of URAGAN SM depends on zenith angle and takes values from 200 to 600 MeV.

For the analysis, FD registered in 2006–2011 by muon hodoscope URAGAN with amplitude of decrease $A_{FD}$ more than ~ 0.5 % were selected. Time series of muon hodoscope URAGAN and neutron monitors were examined, and "difficult" FD (with several FD overlapping during phases of counting rate decrease) were excluded. Only FD with non-distorted intervals more than one day before and after FD onset were selected. Altogether, 33 FD were chosen for the analysis (2006 – 5 FD, 2007 – 2 FD, 2008 – 4 FD, 2009 – 4 FD, 2010 – 6 FD and 2011 – 12 FD). Measurements were conducted mainly during the period of minimum of solar activity what explains relatively poor statistics.

3. Method of FD analysis in the flux of muons registered in the hodoscopic mode

For the analysis of counting rates, as integral ones so in different angular intervals, the technique of determination of basic characteristics of Forbush decreases which is based on the sequential averaging of counting rates before and after the FD for different time intervals considering various trends was used [3]. With its help, the basic parameters characterizing the FD were obtained: the amplitude of the decrease of the counting rate of the detector during the FD ($A_{FD}$), times of the decrease and recovery, the slope of the counting rate before and after FD, etc. These characteristics were obtained both for integral counting rate and for five zenith-angle intervals. For each interval of angles, the mean logarithmic energies of primary protons ($E_{ln}$) contributing to the changes in the muon hodoscope counting rate during FD have been calculated with the use of the CORSIKA package: 14.7 GeV, 15.5 GeV, 17.5 GeV, 19.7 GeV and 25.3 GeV respectively [6]. Analysis of the energy spectrum of cosmic ray modulation during FD was based on the dependence of $A_{FD}$ on $E_{ln}$. These dependences were fitted by a power function $E_{ln}^{\alpha}$.

The studies of the dynamics of the amplitude spectrum index $\alpha(\tau)$ at different stages of the event (the decrease, the minimum and the recovery), which correspond to different phases of the influence of heliospheric disturbances on the flux of cosmic rays, are of a special interest. A similar study using data of neutron monitors and a muon telescope was carried out earlier [7]. The index of the energy spectrum of decreases was estimated from the URAGAN data with increments of 40-60 minutes. The amplitudes of the decrease at different moments of time $\tau_i$ were determined as the differences between the daily average counting rate before the decrease and the averaged over 40 or 60 minutes counting rates on $i$-th steps.

For a quantitative description of the deformation of the angular distribution of the flux of cosmic rays during Forbush decreases, the horizontal projection of the relative anisotropy vector of the muon flux $r_h$ [8] which characterizes the lateral shift of muon flux angular distribution was used. For the analysis of two-dimensional dynamics of muon flux variations during the FD, the projections of the relative anisotropy vector of the muon flux to the South and East ($r_S$ and $r_E$, respectively) were used.

4. Results of studying of FD characteristics in muon flux

On the basis of the described methods of the analysis of FD registered in muon flux in the hodoscopic mode, the basic parameters characterizing the decrease of counting rate and also energy, angular and temporal characteristics of 33 Forbush decreases were studied. Mean amplitude of the decrease in analysed events estimated from the integral counting rate is $\sim 0.8 \pm 0.4$ %. For all FD, the amplitude spectrum indexes $\alpha$ were calculated, and for majority of them the absolute values of $\alpha$ are close to a unit, mean value of $\alpha$ is $\sim -0.97$, RMS deviation is $\pm 0.41$. 

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Dynamics of amplitude spectrum index $\alpha$ during different phases of FD development was investigated. Examples of its behavior for two FD with largest amplitudes (14 December 2006 and 18 February 2011) are shown in figure 1a by the points. Distributions of weighted-mean values of $\alpha(\tau)$ calculated for all 33 FD for each phase of development are presented in figure 1b.

**Figure 1.** Examples of the temporal behavior of counting rate (black lines) and amplitude spectrum index $\alpha$ (red points) for FD of 14 December 2006 and 18 February 2011 (a) and distributions of weighted-mean values of $\alpha$ estimated for 33 FD for each phase: decrease, minimum and recovery (b).

Mean value of $\alpha$ for the phase of decrease is about $-0.72\pm 0.43$, for the phase of minimum about $-0.91\pm 0.36$, and for the phase of recovery about $-0.90\pm 0.51$ (RMS deviations are indicated). From the obtained distributions, a conclusion follows that no significant difference between $\alpha$ values for different FD phases is observed, in contradiction with results [7].

Investigation of muon flux anisotropy for FD from 2007 to 2011 (29 FD) was performed. It was found that in 19 from 29 FD, the anisotropy during the phase of the decrease significantly exceeded its annual average diurnal variations. In figure 2, correlations between projections of the relative anisotropy vector $r_E$ and $r_S$ during the phase of the decrease for several FD observed in 2011 are presented; $t_1$ is the time of beginning of the decrease and $t_2$ is time of its end. These correlations show the presence of spatial changes of anisotropy and give additional information about FD.

**Figure 2.** Correlations between projections $r_E$ and $r_S$ during the phase of the decrease.

The prognostic potential of developed methods of FD investigation in muon flux registered in the hodoscopic mode was estimated with the help of horizontal projection of vector of relative anisotropy $r_h$. For this goal, 13 FD which can be correlated with corresponding disturbances of solar wind (SW), IMF and magnetosphere were selected. In figure 3 (left), an example of variations of these parameters and dynamics of $r_h$ from 13 to 25 February 2011 (Forbush decreases were registered on 15 and 18
February 2011) is presented. For all 13 FD, the differences between the time of beginning of disturbance in $r_h$ (sharp increase to $\geq 1.2 \sigma$ during 1 hour with a following total increase to more than $2.3 \sigma$) and beginning of the disturbance in solar wind velocity ($\Delta t_V$), in the value of magnetic induction vector $B$ ($\Delta t_B$) and in Dst index (moment of SSC or index decrease) ($\Delta t_{Dst}$) were calculated. All respective distributions are shown in figure 3 (right). From the obtained distributions it follows that, on the average, disturbances of the horizontal projection of the vector of relative anisotropy for selected 13 FD are observed ahead of perturbations in the characteristics of SW, IMF and Dst by about 10 h, though in some events the delay up to 12 h was found. These results are preliminary and will be updated with the accumulation of statistics.

![Figure 3](image-url)

**Figure 3.** An example of variations of solar wind velocity $V_{SW}$, vector of magnetic induction $B$, and its projection $B_Z$ (OMNI data [9]) and dynamics of $r_h$ (left); distributions of $\Delta t_V$, $\Delta t_B$ and $\Delta t_{Dst}$ (right).

### 5. Conclusion

The use of muon hodoscope allows to obtain the amplitude, temporal and angular characteristics of detected FD simultaneously. The study of the behavior of projections of local anisotropy vector $r_h$, $r_E$ and $r_S$ provides additional opportunities for identification of various heliospheric disturbances.

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