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FORBUSH DECREASES DURING 2007 – 2018 ACCORDING TO THE MUON HODOSCOPE URAGAN DATA

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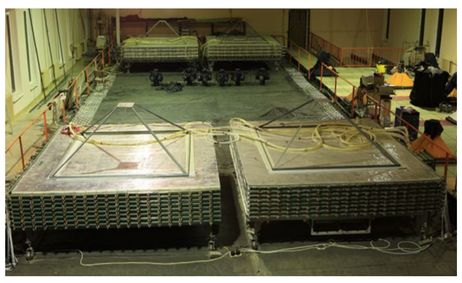
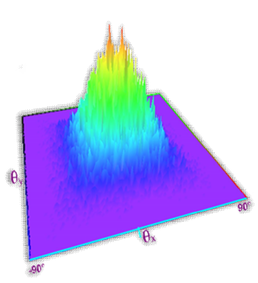
Results of the study of variations of cosmic ray muon flux at the Earth surface during Forbush decreases registered in 2007 – 2018 by means of the muon hodoscope URAGAN are presented. The dynamics of the amplitude spectrum index at different stages (the decrease, the minimum and the recovery), which correspond to different phases of the influence of heliospheric disturbances on the flux of cosmic rays for the period 2012 to 2018, is considered. To investigate possible regularities in the behavior of the projections of the relative local anisotropy vector of the muon flux to the South and to the East (r_S and r_E) during 2007-2018, the distributions of these parameters for four phases (immediately before FD, decrease phase, minimum phase, recovery phase) were calculated.

Muon hodoscope URAGAN

The muon hodoscope URAGAN (MH) is a wide-aperture coordinate-tracking detector intended for detectIon of muons simultaneously from all directions of the upper hemisphere. It is used to study characteristics of muon flux variations as a function of spatial angle. URAGAN consists of four identical supermodules (SM) with total area about 46 m^2.





Track parameters (two projection angles) are reconstructed in real time and tracks are accumulated in a two-dimensional angular matrix for one minute interval. Such matrix is a "muon snapshot" of the upper hemisphere with a minute exposure.

Each SM is assembled of eight layers of streamer tube chambers equipped with two-coordinate system of external readout strips and provides a high spatial and angular accuracy of muon track detection (correspondingly, 1 cm and 0.7°) in a wide zenith angle aperture of 0° – 75°.

Forbush decrease (FD) is one of the 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.

For the analysis, FD registered in 2007–2018 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 "complicated" 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.

Local anisotropy of the muon flux

Local anisotropy vector $\vec{A}$ characterizes the zenith-azimuth distribution of the muon flux for a certain time interval and is the sum of unit vectors, each of which has the direction of the reconstructed track of an individual muon, normalized to the number of events. The summary vector indicates the average direction of the muon flux. A matrix with cell sizes of 1° along the zenith angle (θ) and 4° along the azimuth (ϕ) angle is used to calculate vector $\vec{A}$. The vector can be extended along the directions. We use projections to the geographic south (A_S) and east (A_E), in particular. To investigate deviations from the average direction of the anisotropy vector, we used relative anisotropy vector (a three-dimensional vector), and its projections to the south and east:

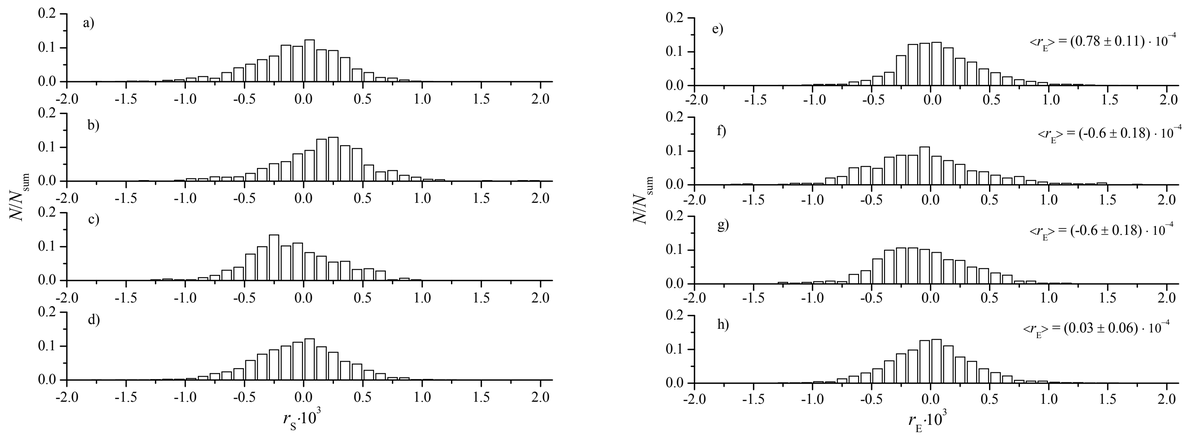
$$\vec{r} = \vec{A} - \langle \vec{A} \rangle,$$

$$r_S = A_S - \langle \vec{A}_S \rangle \quad \text{and} \quad r_E = A_E - \langle \vec{A}_E \rangle$$

where $\langle \vec{A} \rangle$ is the average anisotropy vector calculated for a prolonged time interval. Vector and its projections to the south and east point to the maximum of the muon flux; consequently, the minimum is in the opposite direction. Projections of vectors r_S and r_E are calculated in geographic coordinates. For primary protons (allowing for asymptotic trajectories), the geographic direction from north to south corresponds to the asymptotic direction from east to west, while the one from west to east corresponds to the asymptotic direction from the north to the south.

Results of the analysis of muon flux relative anisotropy variations

To study the regularities in the behavior of the relative anisotropy along the N-S and E-W geographical directions, the distributions of hourly values of the r_S and r_E for all phases of FDs (figures below) normalized to the number of points at each phase were plotted. Such analyses were performed for 75 FDs for the period 2007 to 2018. Earlier, a similar study for the period 2007 to 2012 was conducted.



The distributions of the values of parameters r_S and r_E immediately before FD were symmetrical and lay mainly in the range of (–1.0 to 1.0) ×10^{-3}. A broader range is observed in the decrease phase for both parameters: r_S = (–1.4 to 2.0) × 10^{-3}, while r_E = (–1.7 to 1.8) × 10^{-3}. The values of $\langle r_S \rangle$ = (0.16 ± 0.015) × 10^{-3}. This means that the flux minimum is more often observed from the north, which in turn corresponds to the asymptotic east. r_S is more shifted to the north. In the recovery phase, the distributions of the parameters of relative anisotropy are virtually symmetrical. The muon flux from the geographic south at the decrease stage of the count rate during an FD diminishes less than from the north. At the minimum stage, the opposite is true, corresponding to the variation in the east–west anisotropy of primary cosmic rays. At other stages, the relative anisotropy remains virtually symmetric. The obtained results are in good qualitative agreement with the results for the period 2007 to 2012.

Mean values of parameters and for four FD phases for the periods 2007 – 2012 and 2007 – 2018

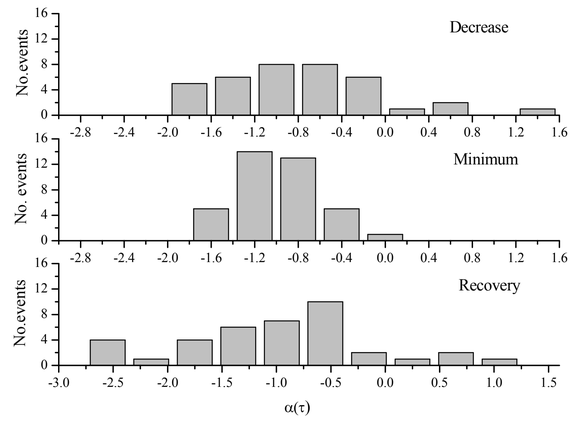
Phase of FD	$\langle r_{E(2007-2012)} \rangle$, 10^{-4}	$\langle r_{E(2007-2018)} \rangle$, 10^{-4}	$\langle r_{S(2007-2012)} \rangle$, 10^{-4}	$\langle r_{S(2007-2018)} \rangle$, 10^{-4}
Before FD	0.40±0.10	0.78±0.11	0.08±0.011	0.50±0.11
Decrease	-0.60±0.25	-0.60±0.18	1.80±0.23	1.60±0.15
Minimum	-0.69±0.15	-0.60±0.18	-0.95±0.17	-0.9±0.2
Recovery	-0.04±0.09	0.03±0.06	-0.26±0.09	-0.4±00.06

Results of studying of FD characteristics in muon flux

The developed method of investigating the dependence of the amplitude of the FD on the energy of primary protons allows to explore the energy characteristics of the FD by means of a single installation in a unified approach and to compare the analyzed events. Minute time resolution of the muon hodoscope URAGAN allows to investigate the dynamics of the amplitude spectrum index at different moments. To do this, the index α of the energy spectrum of FD was calculated with some step (that cannot be smaller than the step of the used data). The amplitudes obtained for various zenith angular intervals, and correspondingly for different mean logarithmic energy is of the primary particles, give possibility to determine the values of spectrum index of the amplitudes of the energy spectrum at different time intervals during and after the FD. The studies of the dynamics of the amplitude spectrum index α(τ) 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, were conducted.

The weighted-mean values of α(τ) of 38 FD registered in muon flux during different phases for the period from 2012 to 2018 were studied. A similar study for the period from 2006 to 2011 for 33 Forbush decreases was carried out earlier. For 38 FD registered in the period 2012-2018, the amplitude spectrum indexes α were calculated, and mean value of α is ~ -0.99, RMS deviation is ±0.28.

Distributions of weighted-mean values of α(τ) for each phase of FD development for the period 2012-2018



The weighted-mean values of α(τ) for three phases of FD development for two time periods (2006 – 2011 and 2012 – 2018) and for 2006 – 2018

<α(τ)>	2006-2011	2012-2018	2006-2018
Phase of decrease	-0.72±0.43	-0.73±0.25	0.72±0.28
Phase of minimum	-0.91±0.36	-0.98±0.08	0.94±0.37
Phase of recovery	-0.90±0.51	-0.98±0.2	0.94±0.55

The obtained distributions show that there is no significant difference between α values for phases of minimum and recovery. The values of spectrum indexes α obtained for the periods 2006 – 2011 and 2012 – 2018 show a good agreement.

Conclusion

The analysis of 75 Forbush decreases registered by the URAGAN showed that the changes in the relative anisotropy of the muon flux are observed mainly at the phases of decrease and minimum and, on the average, correspond to the E-W primary cosmic ray anisotropy variation, what is in good qualitative agreement with the results obtained for the period 2007 to 2012. The obtained distributions of weighted-mean values of α(τ) for each phase of FD development for the period 2012 to 2018 show that there is no significant difference between α values for phases of minimum and recovery in muon flux registered by MH URAGAN.

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