Analysis of Forbush decrease of 18 February 2011 in muon flux

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Abstract: Results of the study of variations of cosmic ray muon flux during Forbush decrease of 18 February 2011 detected by means of muon hodoscope URAGAN are presented. The dependence of the decrease amplitude on the primary particle energy in the region above 10 GeV is obtained from the muon flux angular distribution. The changes of this dependence at different temporal stages of the Forbush decrease are analysed. On the basis of two-dimensional angular variations of muon flux, the values of horizontal projection of local anisotropy vector and unique “muon images” of modulation of cosmic rays are obtained. Parameters of physical processes in the heliosphere during this Forbush decrease are discussed.

Keywords: cosmic ray muons, Forbush decrease, muon hodoscope

1 Introduction

Variations of secondary cosmic rays observed at the Earth’s surface are an integral result of various solar, heliospheric, magnetospheric and atmospheric phenomena. A clear example of the effect of solar activity on cosmic rays are Forbush effects (FEs) [1], also called Forbush decreases (FDs), i.e., sharp decreases of the flux of cosmic rays (CR) at ground level due to deviations of charged particles induced by inhomogeneities of the interplanetary magnetic field and shock waves in the solar wind. Studies of variations of cosmic rays during these effects are carried out basing on the global network of neutron monitors and the network of muon detectors [2]. Investigations of FD in the muon flux are of a special interest, since their studies open possibility of detection of heliospheric disturbances responsible for modulation of high-energy cosmic rays, and the use of new detectors – muon hodoscopes – allows obtain spatial and angular characteristics of CR modulation using just one facility.

Muon hodoscope URAGAN [3] detects cosmic ray muons in a continuous mode since May 2005. To study variations of muon flux at the time of FDs, a comprehensive method that allows investigate their energy, angular, and temporal characteristics has been developed. This technique was applied to 17 FDs recorded by the muon hodoscope over the period 2005 – 2009 [4]. This period was characterized by a low solar activity. Most of FDs detected with the URAGAN had amplitudes less than 1%, and in only three events (8 and 15 May 2005 and 14 December, 2006) the amplitude of the decrease in muon flux was 2 – 3%.

This paper presents the results of the study of energy, angular and temporal characteristics of one of the strongest events over past four years, FD of February 18, 2011 recorded by the muon hodoscope URAGAN.

2 Equipment and experimental data

The muon hodoscope URAGAN consists of independent supermodules (SMs) and makes it possible to register particles in a wide range of zenith angles (from 0 to 80°) with a spatial and angular resolution of about 1 cm and 0.8°, respectively. It allows to study variations of muon flux as in an integral mode, which gives changes in the total count rate, and in hodoscopic mode, which provides simultaneous measurements of muon flux from different directions of the celestial hemisphere. Data of URAGAN hodoscope represent the sequence of matrices containing the numbers of particles in the cells of zenith and azimuth angles, or projection angles \( \theta_z \), \( \theta_h \) of the muon track (in a local coordinate system). Variations in the muon flux during FDs were investigated using both the integral count rate, summed over three SMs (averaged 10-minute data corrected for barometric and temperature effects [5]), and the count rate for five zenith-angular ranges: 0°–17°, 17°–26°, 26°–34°, 34°–44°, and over 44°, the boundaries of which were determined by the requirement of nearly
equal statistical provision. Threshold muon energies depend on zenith angle and vary from 300 to 600 MeV.

3 FD of February 18, 2011

Forbush decrease of 18 February 2011 was caused by the most powerful since 2006 solar flare of class X2.2, which occurred on February 15, 2011 in active region NOAA AR 11158, located in the southern hemisphere of the Sun. Solar flare occurred near the center of the solar disk, in front of the Earth, and was accompanied by large emissions of the plasma. According to satellite measurements of ACE [6], the perturbation was recorded on 18/02/2011 at 00:00 (UT time) as an increase of the solar wind velocity from 300 to 600 km/s, as well as the perturbation of interplanetary magnetic field and increase of plasma density and temperature. Fig. 1 shows the changes in solar wind velocity, interplanetary magnetic field (according to ACE) as well as variations of muon flux measured by muon hodoscope URAGAN over the period from 13 to 27 February 2011, and data of Moscow neutron monitor (MNM) [7] which has the same threshold rigidity as the URAGAN hodoscope (2.4 GV).

It should be noted that before FD of February 18 a small FD occurred on 15 February, which was caused by a preceding M-class solar flare on February 13, 2011. Perturbation of the IMF determined by means of changes in solar wind velocity and vector of the interplanetary magnetic field was found on 14/02/2011 at 13:00, the reaction in muon flux was observed on 15/02/2011 at 00:00, i.e. 11 hours later. On February 18, sharp changes of cosmic ray intensity occurred almost simultaneously with changes in the parameters of the interplanetary magnetic field and solar wind velocity. At the beginning, the decrease in the muon flux was recorded by the muon hodoscope on 18/02/2011 at 2:40, in the neutron flux (according to the MNM) at 3:40. This indicates for a high-power heliospheric event, which affected high-energy component of cosmic rays. Geomagnetic disturbances on the Earth were recorded as SSC on 18/02/2011 at 5:00.

The amplitude of the decrease in the integral count rate of URAGAN (determined as described in [8]) was 1.35%±0.11% while in the rate of MNM 4.22%±0.18%, that is, for FD of 18 February 2011, \( A_{\text{FD}}^{\text{URG}} \) \( \approx 0.31 A_{\text{FD}}^{\text{MNM}} \).

4 Energy characteristics of muon flux changes

Analysis of the energy spectrum of modulation of cosmic rays during Forbush decrease is based on the analysis of the dependence of amplitudes of the decrease on median energy of primary protons \( E_{0.5} \) contributing to changes in the count rate of the muon hodoscope in five zenith-angle intervals listed above, for which values of \( E_{0.5} \) are 13.4, 14.3, 16.2, 18.3 and 24.1 GeV, respectively [9]. For all angular intervals, the amplitudes of the decreases in count rate were determined by means of a unified technique, and their dependence on \( E_{0.5} \) was constructed; then this dependence was fitted by a power function \( E^\alpha \) (Fig. 2a). For the comparison, a similar dependence and its approximation for FD of 14 December 2006 are shown in Fig. 2b; for that, data of two URAGAN SMs operated in December 2006 have been used.

![Figure 1](image1.png)

**Figure 1.** From top to bottom: solar wind velocity and the values of the vectors of IMF \( (B_t, B_z) \); count rate of the URAGAN; count rate of the MNM.

![Figure 2](image2.png)

**Figure 2.** Dependence of decrease amplitude on median primary particle energy for FD of February 18, 2011 (a) and of December 14, 2006 (b).

Values of the exponents of energy dependence \( (\alpha) \) for both events \( \sim -1 \), which agrees well with results of a similar analysis of 17 FD, recorded by URAGAN in the
period from 2005 to 2009 [4]. It should be noted that FD of 14 December 2006 was stronger compared to February 18, 2011. The decrease amplitude in the integral count rate of URAGAN on 14/12/2006 amounted to 2.62% ± 0.21%. And in Fig. 2b it is clearly seen that at energies around 24 GeV the effect was significant: the decrease in the fifth angular range (44°–75°) amounted to 1.95% ± 0.16%. This suggests that the influence of heliospheric disturbances on cosmic rays extended to energies above 24 GeV. In Fig. 2a, on the contrary, in the same energy region (the same range of zenith angles) the amplitude of the decrease was less. This indicates that in the event of 18/02/2011 the upper energy boundary of the modulation was within the sensitivity range of the detector.

Characteristics of the muon hodoscope URAGAN allow study the temporal dynamics of the exponent of the spectrum of decrease amplitudes. Decrease amplitudes at different points in time \( t_i \), were determined as follows:

\[
A_{FD}(t_i) = \frac{I_b - I(t_i)}{I_b} \times 100\%,
\]

where \( I_b \) is the daily mean count rate before the decrease, \( I(t_i) \) is the count rate at the \( i \)-th step averaged over one hour. These amplitudes obtained for different zenith-angular ranges and, consequently, for different median energies of primary particles make it possible to determine the amplitude spectrum exponents at different phases of FD development: decrease, minimum and recovery. Results of evaluation of \( \alpha \) for FD of February 18, 2011 are represented by dots in Fig. 3, count rate of URAGAN during FD, and the time interval for which the values of \( \alpha \) were obtained is shown in the insert.

5 Spatial and angular variations of the muon flux

The matrix format of the experimental data of URAGAN allows study spatial-angular distributions of muon flux in the form of "muon images". In those, variations of muon flux are expressed as deviations of the count rate in the cells of the matrix from the average values (see Fig. 4). The color gradations in the figures correspond to changes in the intensity of muon flux in standard deviation units. Figure 4 shows the two-dimensional dynamics of hourly average flux of muons during FD of 18 February 2011 from 00:00 to 09:00. Poisson fluctuations are smoothed by means of a 2D Gaussian filter. Thin lines identify North-South and West-East directions. The circles correspond to zenith angles 30°, 45°, 60° and 75°. Statistics of each image is equal to about 15 million tracks. In the figure, two-dimensional angular pictures of changes of the muon flux during the FD and their time evolution are seen. For the quantitative description of these deformations it is convenient to use the vector of relative anisotropy \( r \) (indicated at left upper corners of images), the procedure of calculation of which is described in [10].

Figure 5 shows the dynamics of the horizontal projection of the vector of relative anisotropy of muon flux \( r_h \) and \( Z \)-component of the vector of the interplanetary magnetic field \( B_z \) for events of 15 and 18 February 2011. The figure clearly shows that two perturbations of IMF correspond to two time intervals of increasing \( r_h \) (shadows in the plots); in the first case, the reaction in \( r_h \) was observed before the perturbation of IMF (at 9:00), and in the second one with a 3 h delay. It has to be marked that in both cases (especially for February 18, 2011) after the first peak in \( r_h \) value, repeated perturbations of muon flux anisotropy are observed 22 and 23 h later, while the value of \( B_z \) in these time intervals is practically not disturbed. This effect may be explained by the fact that \( B_z \) is measured by the ACE satellite that registers variations of the interplanetary magnetic field at the Lagrange point L1, and the magnetic field in the ACE neighborhood returned to a nearly quiet level several hours after the heliospheric perturbation had passed. At the same time, the region with a disturbed magnetic field was still not far from the Earth, and corresponding distortions of muon flux angular dependence were recurrently observed during 2–3 days.

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6 Conclusion

High angular and spatial resolution of the muon hodoscope URAGAN has allowed a complex survey of the FD of February 18, 2011 and to explore energy, angular and temporal characteristics of variations of cosmic ray muon flux for this event. The obtained data can be used to test different models of the passage of cosmic rays with energies higher than 10 GeV in the heliosphere and near-Earth space during the IMF disturbances, and to solve various applied problems related to remote monitoring of heliospheric perturbations.

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8 References