Analysis of Forbush decreases detected by muon detectors DECOR and URAGAN

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***Abstract*. Forbush effects detected by muon detectors DECOR and URAGAN (MEPhI, Moscow) during the decrease stage of 23rd solar cycle are studied. Dependences of Forbush decrease amplitudes on effective primary proton energy have been analyzed. "Muon images" of these events obtained by means of the unique muon hodoscope URAGAN are presented. Correlations between Forbush decrease parameters and characteristics of heliospheric disturbances are discussed.**

***Keywords*: Forbush decrease, cosmic ray muons, muon hodoscope**

I. INTRODUCTION

The disturbances of the interplanetary magnetic field caused by solar activity lead to changes of flux and anisotropy of cosmic rays, which often appear as sharp decreases of the flux of secondary cosmic rays at a ground level. This phenomenon called as Forbush decrease (FD) was observed for the first time at the registration of charged cosmic ray flux (mainly muons) at the Earth's surface [1]. However, its further studies for a long time were conducted with neutron monitors. The relatively low energies of primary cosmic rays to which neutron monitors are sensitive and as a consequence considerable amplitudes of the effect are advantages of this approach. However to explore modulations of cosmic rays with energies of tens GeV the possibilities of neutron monitors are somewhat limited. The absence of information about the direction of the arrival of cosmic ray particles is another significant drawback of a neutron monitor.

The appearance of multidirectional muon telescopes [2] and later of muon hodoscopes [3] opened new possibilities in studies of Forbush decreases. The important advantage of muon hodoscope is an opportunity to simultaneously register muons from different directions and to form "muon images" of the sky hemisphere. In this work, a detailed analysis of the Forbush decreases registered in muon detectors DECOR [4] and URAGAN [5] in 2005–2006 is conducted. Main attention is paid to questions of the correlations of variations of the galactic cosmic rays at different energies during FD and parameters of heliospheric disturbances.

II. DETECTORS AND EXPERIMENTAL DATA

The coordinate detector DECOR is deployed around the Cherenkov water calorimeter NEVOD [6]. 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 are located on the cover of the calorimeter water tank and are assembled of eight horizontal streamer tube chamber layers. For the present analysis, coincidences between signals from any side SM and any top SM are used. Such condition provides registration of muons with energy $E > 2$ GeV.

In 2005, a new multipurpose muon hodoscope URAGAN was constructed on the basis of top supermodules. 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 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 the limits from 200 MeV to 600 MeV.

In the present work, eight FD detected by means of these setups in 2005–2006 are examined. In the analysis, 10-min data corrected for barometric effect are considered. To bring down 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.

III. FD AND HELIOSPHERIC PAPRAMETERS

One of the basic parameters which characterize FD is the amplitude of a decrease in the detector counting rate (A_{FD}). Therefore it is important to measure this value with as low as possible uncertainties. For determination of this value for muon detectors it is necessary to take into account diurnal variations and different trends, which change cosmic ray intensity. This problem was solved by introducing a special method of determining the parameters, which characterize variations in the flux of muons during FD [7]. The essence of the method consists in the use of the averaged counting rates of muons before and after FD for different time intervals

TABLE I: The amplitudes of the decreases (A_{FD}), some characteristics of solar events, heliospheric disturbances and geomagnetic storms connected with Forbush effects.

FD	A_{FD}, %	Class of the flare	B_{IMF}, nT	V, km/s	SSC	Dst, nT
14.12.06	3.78 ±0.12	X3.4	20.0	921	+	-146.0
08.05.05	2.71 ±0.13	M1.3	19.3	854	+	-127.0
15.05.05	2.52 ±0.17	M8.0	56.1	989	+	-263.0
13.04.06	1.22 ±0.05	–	19.8	555	–	-111.0
29.11.06	0.91 ±0.12	–	16.1	458	–	-74.0
09.11.06	0.87 ±0.02	C6.5	19.6	537	+	-51.0
14.11.06	0.65 ±0.05	C3.3	7.5	373	–	-13.0
20.02.06	0.35 ±0.02	A7.9	11.7	592	–	-42.0

taking into account different trends. In this case the FD amplitude is defined as the difference between obtained averaged counting rates. For the final evaluation of the amplitude, the average from the calculated values of amplitudes (for different time intervals before and after FD) is considered, and as an error – standard deviation of these amplitudes.

With the above procedure, the basic parameters of FD were determined for eight Forbush decreases registered by the detector URAGAN: the moment of the beginning of the decrease, the moment of the end of the decrease, the amplitude of the decrease (A_{FD}) (see Table I). Besides, some characteristics of solar events, heliospheric disturbances and geomagnetic storms connected with Forbush effects are also presented in the Table.

In the Table I, FDs are listed in the order of the amplitude reduction. As one can see, approximately the same order is observed for solar flare class and for speed of solar wind near the Earth orbit. Less correlations are observed between A_{FD} and parameters of magnetic perturbations (as for IMF as for the Earth magnetic field).

IV. ENERGY DEPENDENCE OF A_{FD}

Muon hodoscope URAGAN makes it possible to measure variations in cosmic ray muon flux simultaneously for different zenith angles. This gives the possibility to investigate FD in cosmic rays at different energies. In order to study A_{FD} dependence on the energy of primary particles the upper hemisphere was divided into five zenith-angular intervals with approximately equal statistics: 0°-17°, 17°-26°, 26°-34°, 34°-44° and more than 44°. For each of eight FD, registered by muon hodoscope URAGAN, the values of amplitudes for these five zenith-angular intervals were determined.

In order to relate muon energy and energy of primary particles, it is necessary to know the coupling functions for muon hodoscope [8]. Knowing the yield function of the detector $P(E,\theta)$ and assuming that the decrease of the flux of primary cosmic rays for FD has the form $\Delta J_p/J_p \sim R^{-1}$ (here R is the rigidity) [9], it is possible to calculate the response function of muon hodoscope $G(E,\theta)$ and to determine the range of energies of primary protons which give main contribution in decreasing of counting rate of the detector. These functions are given in Fig. 1a for vertical direction ($\theta = 0°$). Examining the response function as the energy distribution of primary protons (Fig. 1b) it is possible to calculate median energies of primary cosmic rays (CR).

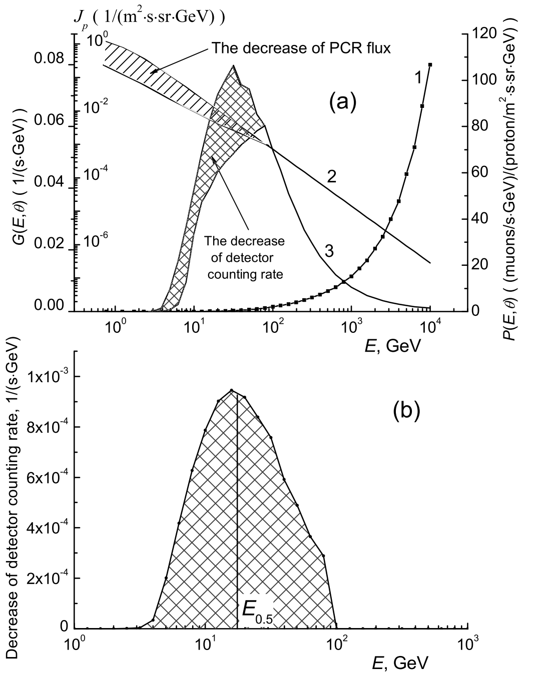


Fig. 1: Example of coupling functions for muon hodoscope at vertical direction (a): 1 – yield function $P(E,\theta)$; 2 – spectrum of primary cosmic rays; 3 – response function $G(E,\theta)$; (b): response function of the detector for decrease of primary cosmic ray intensity.

Median energies of primary protons ($E_{0.5}$) which give the contribution to counting rate of the muon hodoscope in zenith-angle intervals listed above were calculated and their values are equal to: 13.4 GeV, 14.3 GeV, 16.2 GeV, 18.3 GeV and 24.1 GeV, respectively. With the aid of the response function $G(E,\theta)$ it is also possible to estimate primary cosmic ray energy range giving 90% contribution to the reduction of the counting rate of the muon hodoscope: it is 5–51 GeV for the first angular interval and 8.6–66 GeV for the fifth angular interval.

For the eight events, the dependences of FD amplitude on the median energy of primary protons were constructed and approximated by power-law function $E^{-\alpha}$ (Fig. 2). In some cases, A_{FD} estimated by DECOR data was added ($E_{0.5} = 28$ GeV). Values of α are given in Table II; in the next column, χ^2 values are presented.

Notably, only for three FD the index α is close to 1. Possibly this indicates that the index of galactic cosmic

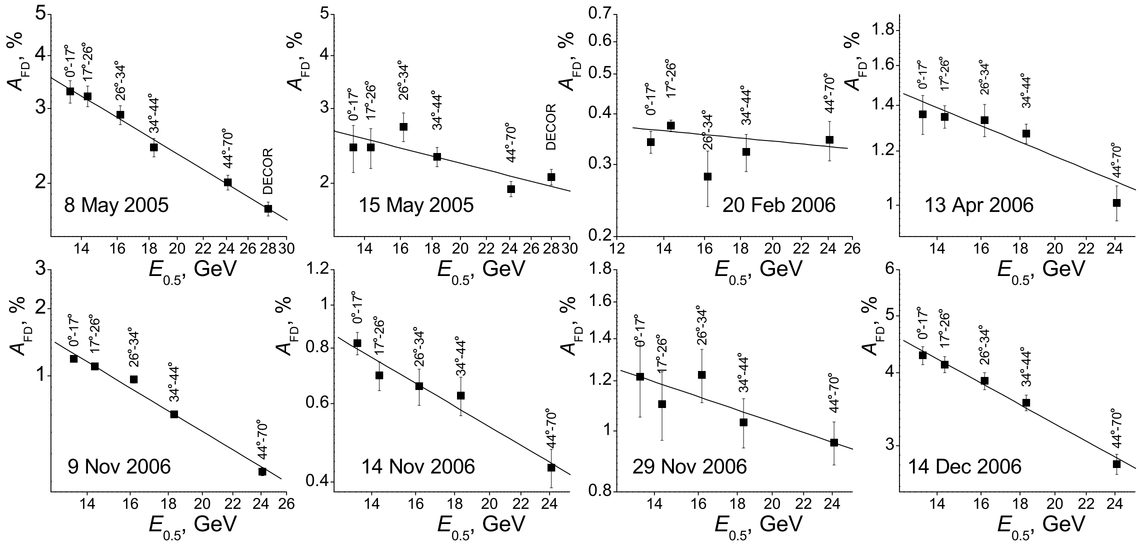
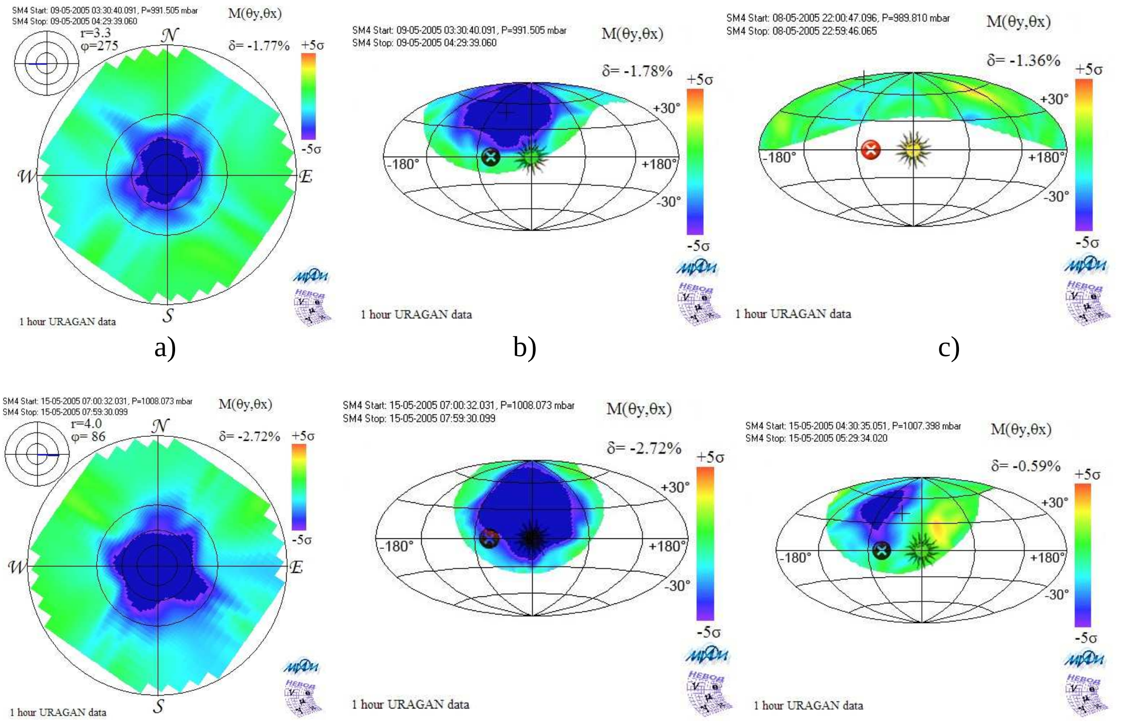


Fig. 2: Dependence of FD amplitudes on the median energy of primary protons for five zenith-angular intervals.



a) b) c)

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Fig. 3: Muon images: a) at observation point; b) on the magnetopause in GSE coordinate system at the moment of maximum decrease; c) the same as b, but at the moment of maximum anisotropy and with the correction to first-order distorsion of zenith-angular shape.

ray modulations lies in a sufficiently wide range of values.

V. MUON IMAGES OF FD

Main peculiar feature of muon hodoscope URAGAN is the possibility of measurements of the spatial-angular structure of muon flux. Excellent angular resolution allows 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 track 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 variations, 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 Figs. 3a, the examples of 2D-images at observation point are presented. To smooth Poisson fluctuations the data were averaged over 60-minute intervals and a special Fourier filter was also used. A scale at the figures denotes values of muon intensity changes in standard deviation units. Tints represent excess or deficit of muons from a certain direction. Thin lines identify North-South and West-East directions. 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 pictures of the decrease of the muon flux during the Forbush decrease are seen. For the quantitative description of these deformations it is convenient to use a vector of anisotropy $\vec{r}$ (indicated at the left upper corner of images), the procedure of calculation of which is described in [10].

In Fig. 3b and Fig. 3c the projections of muon images to the boundary of magnetosphere using asymptotic directions for each angular cell [11] are shown in GSE system. A thin right cross on GSE map denotes vertical direction in muon hodoscope. Circle with X-sign denotes the direction to IMF line (average GSE longitude is approximately equal to -45°); the Sun direction is pointed in the centers of images. Based on examples of two FD of May 8 and May 15, 2005 it is possible to directly observe the angular shape of decrease in the cosmic rays during FD, and also the deformation of the angular flux distribution against the background of total decrease.

The Figs. 3b correspond to the moments of the maximal decrease, and figures Figs. 3c – to the moments of the maximal anisotropy of the muon flux. To eliminate the large-scale drop of cosmic ray intensity in GSE-images, in Figs. 3c a correction to first-order distortion of zenith-angular shape was made. This procedure makes it possible to see second-order deviations from total decrease of muon flux reflecting anisotropy of primary cosmic rays. The maximum values of anisotropy vector module $r_{\max}$ in the FD periods for all eight events are given in Table II (in its standard deviations).

TABLE II: Values of α, χ^2 and $r_{\max}/\sigma_r$.

FDs	α	χ^2	$r_{\max}/\sigma_r$
8 May 2005	-0.88±0.07	0.51	5.1
15 May 2005	-0.37±0.11	1.29	13.2
20 Feb 2006	-0.16±0.20	1.25	4.5
13 Apr 2006	-0.46±0.12	1.08	4.9
9 Nov 2006	-2.01±0.07	2.01	5.4
14 Nov 2006	-1.01±0.19	0.74	3.0
29 Nov 2006	-0.41±0.21	0.62	4.5
14 Dec 2006	-0.72±0.08	0.66	7.2

It is evident from the figures that on May 8, 2005 the cloud of plasma evenly covered the field of view of the detector, and on May 15, 2005 the essential anisotropy in the flux of muons was observed, which is clearly seen after elimination of large-scale decrease of zenith-angular dependence of muon flux (Fig. 3c).

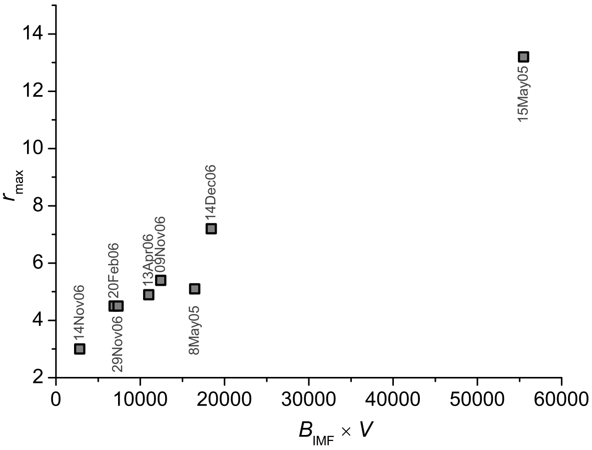

Fig. 4: Correlations between vector of anisotropy and the product of IMF induction and of solar wind speed.

We have also examined correlations between power-law approximation index α (see section IV) and various parameters of heliosphere disturbances, but did not find pronounced dependences. As for the value of anysotropy, evident correlation between $r_{\max}$ and $B_{\text{IMF}} \times V$ is found (Fig. 4). Possibly, with increasing of FD statistic other correlations will be found.

VI. CONCLUSION

Muon hodoscopes open new possibilities of studies of FD and their relation with different heliospheric phenomena. We hope that developed approaches will be very useful during the next 24th cycle of solar activity.

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REFERENCES

[1] S.E.Forbush, Phys. Rev., 1937, v.51, p.1108.
[2] Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya Multi-Directional Muon Telescope, http://www.stelab.nagoya-u.ac.jp/ste-www1/div3/muon/dbtext22.pdf
[3] V.V.Borog et al., Proc. 24th ICRC, Roma, 1995, v.4, p.1291.
[4] M.B.Amelchakov, V.M.Aynutdinov, N.S.Barbashina et al., Proc. 27th ICRC, Hamburg, 2001, v.3, p.1267.
[5] N.S.Barbashina, D.V.Chernov, R.P.Kokoulin et al., Instr. Experim. Tech., 2008, v.51, No.2, p.180.
[6] V.M.Aynutdinov, V.V.Kindin, K.G.Kompaniets et al., Astrophys. and Space Sci., 1998, v.258, p.105.
[7] N.S.Barbashina, A.N.Dmitrieva, K.G.Kompaniets et al., Bulletin of the Russian Academy of Sciences: Physics, 2009, v.73, No.3, p.343.
[8] E.I.Yakovleva, A.G.Bogdanov, A.N.Dmitrieva et al. Bulletin of the Russian Academy of Sciences: Physics, 2009, v.73, No.3, p.357.
[9] L.I.Dorman, Cosmic Rays Variations and Space Exploration, North-Holland Publishing Company, Amsterdam, 1974.
[10] D.A.Timashkov et al, Proc. 31st ICRC, Lodz, 2009, SH.2.2, ID891.
[11] D.A.Timashkov et al, Proc. 21st ECRS, Koshice, 2008, ID4.04.