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Muon diagnostics of the heliosphere – present status

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Abstract: Muon diagnostics is a technique for the remote monitoring of various dynamic processes in the heliosphere and the Earth's magnetosphere and atmosphere, based on the analysis of spatial and angular variations in the flux of muons detected simultaneously from all directions in the upper hemisphere. Approaches to data analysis and some of the results from studies of the extra-atmospheric processes detected using the URAGAN muon hodoscope are discussed.

Keywords: muons, muon diagnostics, cosmic ray variations, solar-terrestrial physics, Forbush decrease, GLE

1 Introduction

Muon diagnostics (MD) is a new direction in the development of the world environmental observation system based on penetrative ability of cosmic ray muons. Muon flux is formed in the atmosphere at altitudes 15-20 km and is sensitive to the changes of main thermodynamic atmospheric parameters as well as to the processes in the near-heliosphere and the magnetosphere of the Earth, related with the activity of the Sun. Variations of muon flux at the Earth's surface caused by these reasons are the object of the study of muon diagnostics. The main MD objective is early recognition and forecasting of the development of destructive phenomena of atmospheric and extra-atmospheric origin [1, 2]. This problem has not been solved yet, despite of enormous amount of data related to our space environment obtained with ground-level and space-born apparatus. One of the reasons for this is the existence of a spatial gap between the data from astronomical observations of perturbations in the Sun and its corona and the data from satellites on perturbations in the interplanetary magnetic field (IMF) in near-Earth space. New possibilities are opened with the use of muon hodoscopes [1, 2]. Since muons (in contrast to neutrons) keep primary particle direction, the opportunity to measure primary cosmic ray variations from various directions appears. Moreover, muon hodoscopes allow detect muons simultaneously from any direction of upper hemisphere and form "muon images" of the disturbed regions.

2 Muon hodoscope URAGAN

The muon hodoscope URAGAN is currently operating in MEPhI (Moscow) [3, 4] and represents four eight-layer assemblies-supermodules on the basis of streamer tubes (1 cm^2 cross-section, 3.5 m length) with external two-coordinate data readout system. It has 46 m^2 total area, sufficient to provide high statistics: more than 5000 muons per second. The supermodule (SM) response contains information about muon track in X- and Y-projections. Two projected angles are reconstructed in real time mode and are accumulated in one-minute 2D-directional matrices. The bell-like shape of every matrix represents angular distribution of muons detected during one minute exposure from any directions of upper hemisphere. The size of the angular cells in URAGAN matrix data was chosen $2^\circ \times 2^\circ$ (in two projected zenith angles). Sequence of such matrices represents the filming of the upper hemisphere in "muon light". To study muon flux variations, for every cell of the angular matrix the average number of muons (estimated during preceding 24 hours and corrected for atmospheric pressure and temperature [5]) is subtracted, and results are divided by standard deviations. Obtained data array is a "muon snapshot" of the upper hemisphere with 1-minute exposure. As a quantitative characteristics of angular muon flux variations, the local anisotropy vector is used which indicates the average arrival direction of muons. Local anisotropy vector $\vec{A}$ is defined as the sum of unit vectors, each representing the direction of the individual track, normalized to the total number of muons [6]. In addition, the value of the vector of the relative anisotropy of $\vec{r} = \vec{A} - \langle\vec{A}\rangle$, where $\langle\vec{A}\rangle$ is the local anisotropy vector averaged for a long time period, and its projection on the horizontal plane r_{h} are considered. For the study of dependences in the azimuth anisotropy of muon flux it is suitable to use projections of the vector $\vec{A}$ directed to the South and East (correspondingly, A_{S} and A_{E}) [6, 7]. Analysis of the changes (variations) of the matrix shape related with an influence of different modulation processes in the heliosphere and Earth's magnetosphere and atmosphere gives a possibility to study development of these phenomena directly on the basis of URAGAN data.

3 Analysis of URAGAN data

URAGAN has been operating continuously since 2006. Variations in the integral muon counting rate over the period 2007-2012 were investigated. Data (about $4{\cdot}10^{11}$ muons) were obtained by summation of counting rates of three SMs of the URAGAN for zenith angle range $25^\circ \leq \theta < 76^\circ$. The frequency spectrum obtained as a result of the Fourier analysis of time dependence of hourly average counting rate is shown in figure 1. This analysis shows the presence of annual, 27-day, diurnal and semi-diurnal variations [8]. The diurnal correlation of projections A_S and A_E of the local anisotropy vector $\vec{A}$ averaged by year (2007-2012) are presented in figure 2. In figure 3, correlations between the monthly averaged horizontal projection of the relative anisotropy vector r_h with IMF induction (B) and number of sunspots (R) for the period 2007-2012 are shown. From the figures it is clearly seen that during 2007-2012 the dynamics of the changes of average monthly value r_h is comparable with the dynamics of changes in the number of sunspots R and the interplanetary magnetic field induction derived from the OMNI database [9].

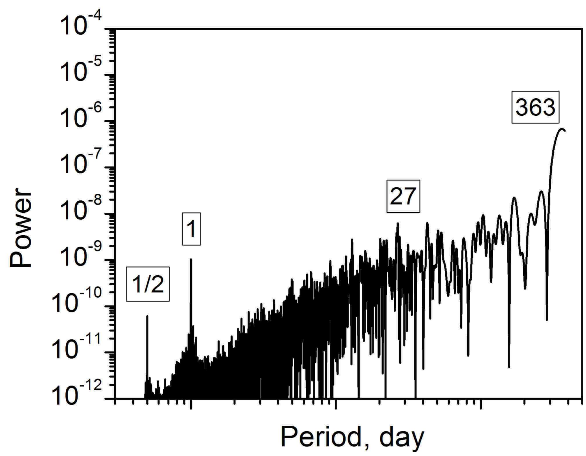

Figure 1: Fourier power spectra of the time sequence of muon counting rate. In the boxes, the values of the periods (in days) are specified for corresponding peaks.

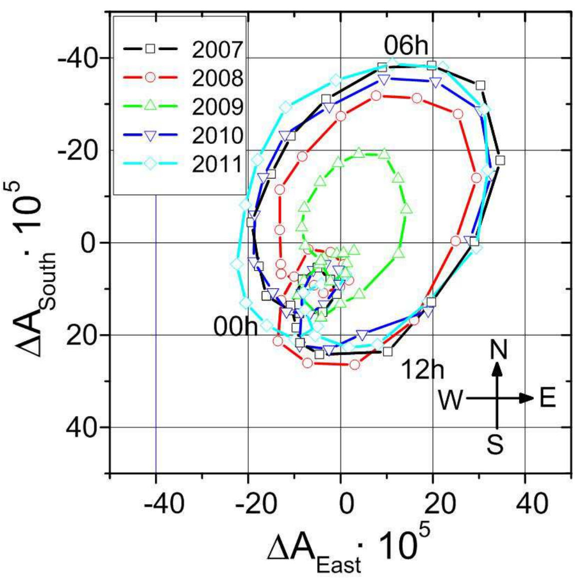

Figure 2: Correlations of projection A_S and A_E in annual average diurnal cycle.

3.1 Monitoring of heliospheric perturbations

Analysis of the PCR flux variations related with perturbations in the heliosphere requires comparison of variations in the muon counting rate at the level of observation and variations in CR intensity at the boundary of the magnetopause. The corresponding calculations for the coupling functions were performed for the URAGAN muon hodoscope, and asymptotic directions were obtained for all of the zenith angles accessible to the hodoscope and their related threshold primary energies [10, 11]. This allowed us to evaluate the angular PCR variations at the magnetopause boundary that were responsible for the angular muon flux variations recorded by the URAGAN. The abilities of the URAGAN muon hodoscope were demonstrated while recording the GLE#70 solar proton event on December 13, 2006. The ground-level enhancement in the muon counting rate caused by the solar flare was recorded by two URAGAN SMs at a level of six sigmas (for ten-minute intervals). The maximum increase was observed at 03:00 UTC. Based on the analysis of 2D muon flux images, the proton spectrum was evaluated for the GLE event by solving the inverse problem, using the calculated yield functions for the muon hodoscope: $J_p(E) = 65E^{-5.5\pm2.8}$ [$\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$] [12]. It was also shown that the effective energies of primary particles responsible for the increase were about three times higher for the muon hodoscope than for the Moscow neutron monitor, but not greater than 30 GeV. Another example of muon diagnostics capabilities is the recording of Forbush decreases (FD). Unlike neutron monitors, muon hodoscopes allow the angular and energy characteristics of FDs and their time dependences to be investigated on a single setup.

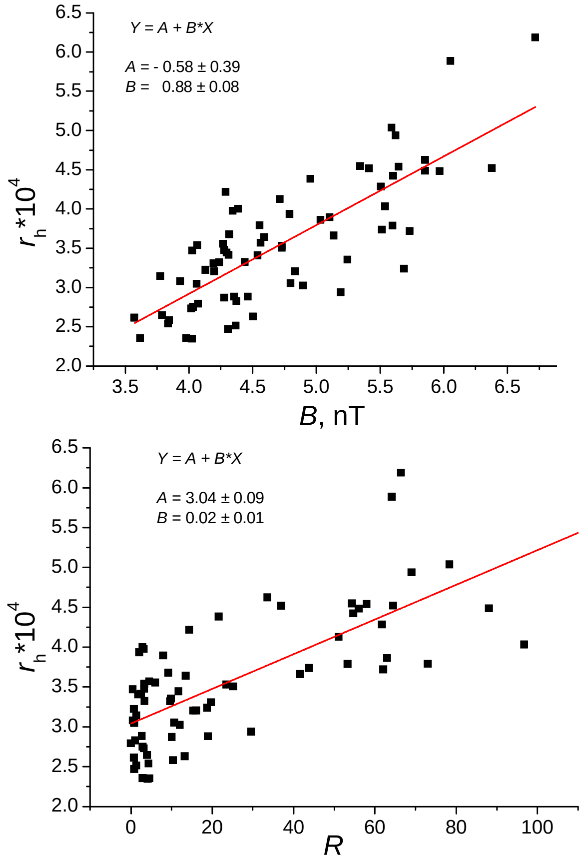

Figure 3: Correlations of monthly averaged horizontal projection of the relative anisotropy vector r_h with magnetic induction (top) and the number of sunspots (bottom).

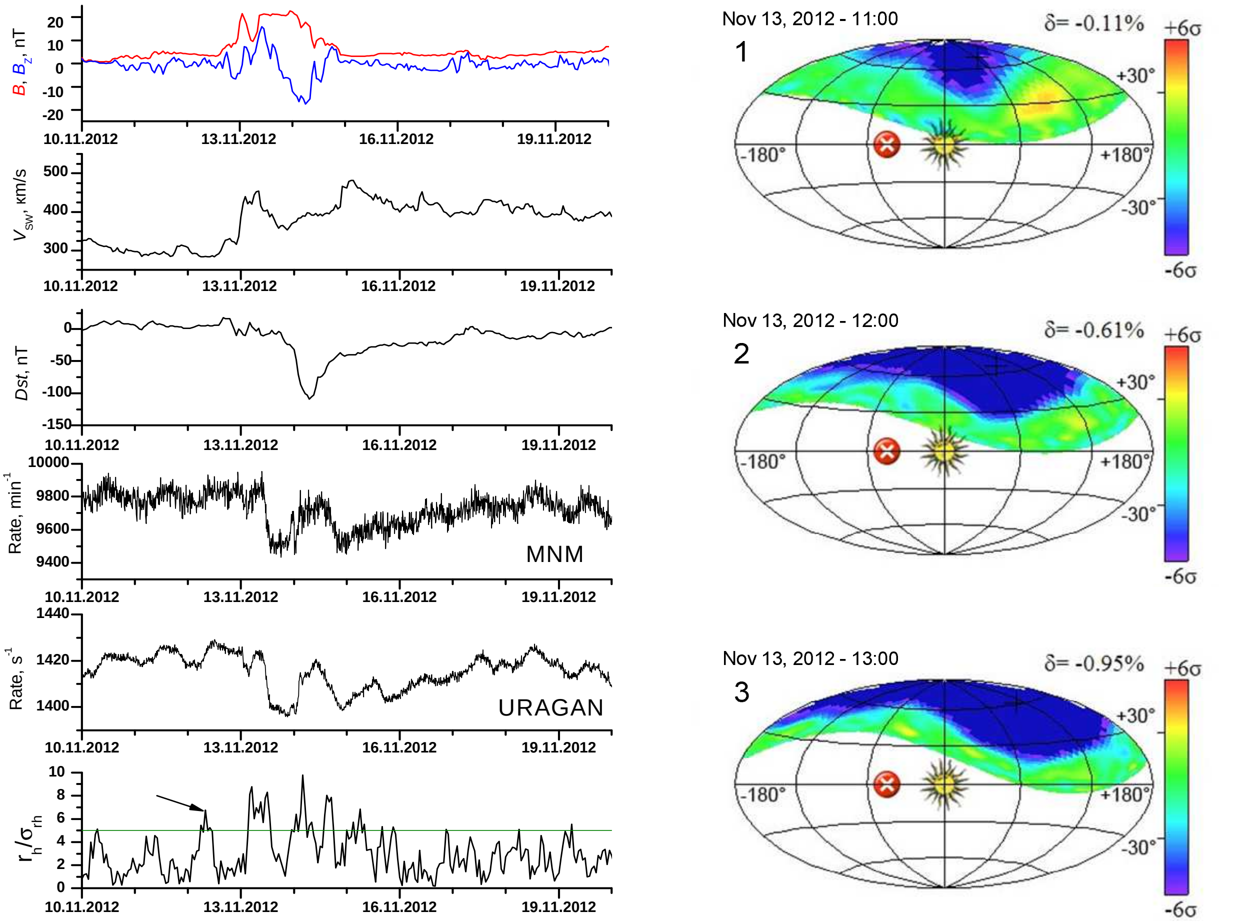

Figure 4: Variations in the CR muon flux during the FD on November 13, 2012. Left (top to bottom): IMF vector (B, B_z), speed of the solar wind, *Dst*-index, MNM counting rate, URAGAN counting rate and r_h variations. Right: GSE images for the moments during CR muon intensity decreasing. The circles with crosses show the direction of the solar magnetic line. The direction to the Sun is indicated at the center.

Analysis of the URAGAN time series data showed that the angular muon flux variations during FDs were most effectively described using the parameter r_{h}. Figure 4 presents the example of heliospheric perturbation recorded by ground-level detectors (MH URAGAN and Moscow neutron monitor, MNM) and by space-born apparatus over the period November 12-14, 2012. It was an ordinary heliospheric event. A pair of minor CMEs were launched on Nov. 9th and 10th, respectively, and possibly merged into a single cloud before they reach the Earth on Nov. 12th. NOAA estimated a 55% chance of polar geomagnetic storms. But this minor event caused sufficiently strong perturbation of magnetosphere ($Dst \sim -110$ nT). Besides the URAGAN and MNM counting rates, the data on the IMF characteristics, the solar wind, *Dst* index and anisotropy parameter r_{h} are also shown in the picture. Variations in the muon flux during FDs were investigated using the counting rate, summed over three SMs and corrected for barometric and temperature effects. Analysis of temporal changes of these parameters revealed that the IMF perturbation beginning was fixed November 12 at 16:00 UT ($B = 6.2$ nT), of solar wind - November 12 at 22:00 ($V_{\mathrm{SW}} = 316$ km/s), of the magnetosphere of the Earth - November 13 at 20:00 ($Dst = -21$ nT). Decreasing of the MNM and URAGAN counting rates (FD beginning) is observed in the period from 10:00 to 14:00 November 13. The comparison of the data of MNM and URAGAN shows a good agreement. The changes of anisotropy of muon flux exceeding statistical fluctuations of the value $r_{\mathrm{h}}/\sigma_{r_{\mathrm{h}}}$ took place on November 12, 2012 at 8:00 UT (arrow in the bottom frame), i.e. 8 h earlier than the IMF parameter changes. Heliospheric events can be studied in more detail using their GSE images. At the right of the figure, there are images obtained during the period of FD counting rate decreasing. To obtain a GSE image, the every angular cell of muon snapshot was projected onto the magnetopause using asymptotic directions transformed to the GSE system.

As a whole, the analysis of typical FDs detected by URAGAN in hodoscopic mode reveals that disturbances of the horizontal projection of the vector of the relative anisotropy of muon flux, on average, are observed ahead of perturbations in the characteristics of the solar wind, IMF and in the magnetosphere by $\sim 10 - 12$ h and can be used as a predictor of magnetospheric storms.

4 Conclusions

The use of cosmic ray muons and muon hodoscopes, which allow muon filming of the extra-atmospheric space, opens up new prospects for the remote monitoring of space. Even when measured with a single wide-aperture hodoscope, an analysis of muon flux anisotropy during heliospheric perturbations can yield unique information on the structure and dynamics of these events and to compare predictions of various models of heliospheric processes with direct measurements of muon flux variations.

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