# LARGE AREA HODOSCOPES FOR MUON DIAGNOSTICS OF HELIOSPHERE AND EARTH'S MAGNETOSPHERE

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Abstract. Muon diagnostics is a technique for remote monitoring of active processes in the heliosphere and the magnetosphere of the Earth based on the analysis of angular variations of muon flux simultaneously detected from all directions of the upper hemisphere. To carry out muon diagnostics, special detectors – muon hodoscopes – which can detect muons from any direction with good angular resolution in real-time mode are required. We discuss approaches to data analysis and the results of studies of various extra-terrestrial processes detected by means of the wide aperture URAGAN muon hodoscope.

Keywords: cosmic rays, muons, muon hodoscope, angular variations of muon flux, solar, terrestrial connections, heliosphere, magnetosphere.

## 1. Introduction

During powerful solar events, e.g. coronal mass ejections (CME), clouds of magnetized plasma disturb interplanetary magnetic field (IMF) and can produce strong magnetic storms in the magnetosphere of the Earth. However, the problem of an early recognition and forecasting of the development of such dangerous phenomena has not yet been solved. The main reason for this is a scarcity of information about the heliosphere conditions between the Mercury's and the Earth's orbits. Solar observations allow to see the moments of the appearance of various events. Space-borne apparatus can give information about heliospheric disturbances 1–2 hours before their arrival on Earth. From this point of view, cosmic rays are a promising tool in the development of the world environmental observation system, based on their penetrative ability. Movement of solar plasma through the heliosphere disturbs the magnetic field, causing modulation of primary CR (see Fig. 1) and correspondtngly of secondary components of cosmic rays (mainly neutrons and muons) generated in the atmosphere. To detect them, a world-wide net of ground-based stations (neutron monitors and muon telescopes) is used. The objective of these observations is to solve the inverse task – a study of dynamic processes in the heliosphere and magnetosphere using cosmic ray variation data. However, neutron monitors can measure integral flux variations only and the information from the whole world-wide neutron monitor net allows to obtain some conclusions about heliospheric processes.

Muons (in contrast to neutrons) keep parent particle directions, and hence there is an opportunity to measure primary cosmic ray variations from various directions. However, muon telescopes do not have sufficient resolution to obtain a spatial picture of the disturbance development in the heliosphere. New possibilities in this field are opened by the use of muon hodoscopes [4, 7], which allow the solution of this task by methods of muon diagnostics [3, 11].

Unfortunately, however, the scheme of cosmic ray application for heliosphere and magnetosphere investigations is not so simple, since the flux of secondary particles at the surface depends not only on the primary cosmic ray flux, but also on the conditions in the atmosphere. For example, muon flux at ground level is strongly related with various thermodynamic processes in the Earth's atmosphere at generation level (barometric, temperature effects) and with more complex wave processes in the low stratosphere (inner gravitational waves of air density, density gradients, etc.) correlated with various turbulent and wave processes of geophysical origin, which are localized in space and time [2]. For reliable recognition of extra-terrestrial phenomena, it is therefore necessary to take into account the variations of muon flux of atmospheric origin.

## 2. Muon hodoscopes

To realize the muon diagnostics, there is a need for wide-aperture muon detectors – hodoscopes, which enable simultaneous measurements of the intensity of
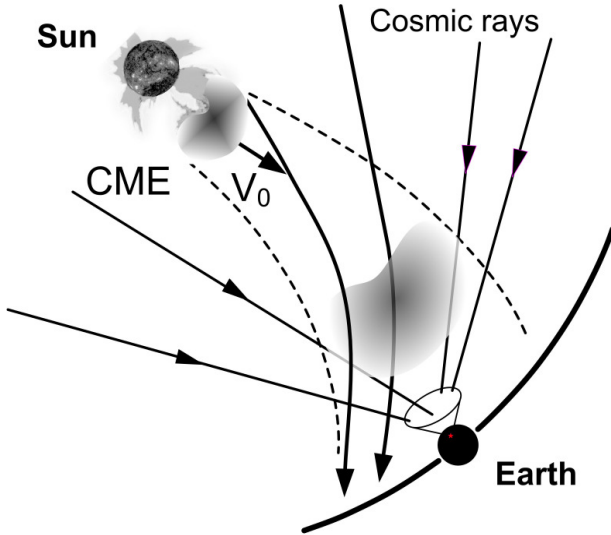
Figure 1. Modulation of primary cosmic rays related with solar activity.

muons from all directions of the upper hemisphere. Such detectors must have angular resolution of muon track reconstruction of the order 1 degree and a large sensitive area to provide necessary statistical accuracy of experimental data for all zenith and azimuth angular bins. The possibilities of muon diagnostics were demonstrated by means of the first hodoscopes: the TEMP scintillation muon detector [7] and the URAGAN hodoscope [4]. Now a new scintillation muon hodoscope with wavelength shifting (WLS) optical fiber light collection is under construction [1]. Since most of the experimental results were obtained at the URAGAN muon hodoscope, we mainly consider them.

URAGAN has been in operation at MEPhI (Moscow, 55.7° N, 37.7° E, 173 m altitude a.s.l.) since May 2005 [4]. It consists of four eight-layer assemblies (supermodules, SM) on the basis of streamer tubes ($1\,\mathrm{cm}^2$ cross-section, 3.5 m length) with external two-coordinate data readout. It has $46\,\mathrm{m}^2$ total area, sufficient to provide good statistics: more than 5000 muons per second. The supermodule response contains information about the muon track in both $x$- and $y$-projections [8]. Two projected zenith angles are reconstructed in real time mode and are accumulated in 2D-directional matrices (zenith and azimuth angles, or a pair of projected zenith angles). A sequence of such matrices provides 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 the preceding 24 hours and corrected for atmospheric pressure and temperature [9] is subtracted, and the results are divided by standard deviations. The obtained data array provides a "muon snapshot" of the upper hemisphere with 1-minute exposure. The size of angular cells in the URAGAN matrix data was chosen 2° × 2° (in two projected zenith angles). The local anisotropy vector is used

as a quantitative characteristic of the angular variations of muon flux. This vector indicates the average arrival direction of the muons. The local anisotropy vector $\mathbf{A}$ is defined as the sum of the unit vectors, each representing the direction of an individual track, normalized to the total number of muons [12]. Projections of the vector of local anisotropy $(A_x, A_y, A_z)$ from the initial matrix data $M$ are defined as:

$$A_x = \frac{1}{N} \sum_{\theta} \sum_{\varphi} M(\theta, \varphi) \cos\varphi \sin\theta,$$

$$A_y = \frac{1}{N} \sum_{\theta} \sum_{\varphi} M(\theta, \varphi) \sin\varphi \sin\theta,$$

$$A_z = \frac{1}{N} \sum_{\theta} \sum_{\varphi} M(\theta, \varphi) \cos\theta,$$

$$N = \sum_{\theta} \sum_{\varphi} M(\theta, \varphi),$$

where $\theta$ and $\varphi$ are the angles corresponding to the matrix cell midpoints, $M(\theta, \varphi)$ is the number of recorded events in a corresponding matrix cell $(\theta, \varphi)$ of the matrix $M$, and $N$ is the total number of events in the angular range that is used. For convenience, the $x$ axis is directed to the South, and the $y$ axis is direcred to the East (see Fig. 2). In addition, the value of the vector of the relative anisotropy of $\mathbf{r} = \mathbf{A} - \langle\mathbf{A}\rangle$, where $\langle\mathbf{A}\rangle$ is the local anisotropy vector averaged for a long time period, and its projection on the horizontal plane $r_{\mathrm{h}}$ are considered.

## 3. Analysis of the URAGAN data

### 3.1. Temporal variations
Variations of the total counting rate of muons measured by means of the URAGAN hodoscope between 2007 and 2011 are presented in Fig. 3. The data in the figure (about $4 \times 10^{11}$ muons) were obtained by summing the counting rates of three supermodules of the URAGAN for zenith angle range $25° \leq \theta < 76°$. The frequency spectrum obtained as a result of the Fourier analysis of the time series of hourly average muon counting rate is shown in Fig. 4. The part of the spectrum with periods from 10 to 40 days is highlighted in the inset.

The analysis of variations of the counting rates shows the presence of annual, 27-day, diurnal and semi-diurnal variations [10]. Figure 5 presents correlations between the diurnal changes of East and South projections of local anisotropy vector. The correlations in the annual average diurnal cycle are clearly seen.

### 3.2. Analysis of Forbush decreases
For the analysis of variations of the muon flux at the time of Forbush decreases (FD) detected by the URAGAN, an experimental technique has deen developed that allows their energy, angular, and temporal characteristics to be investigated [5]. Variations in the muon flux during FDs were studied using both
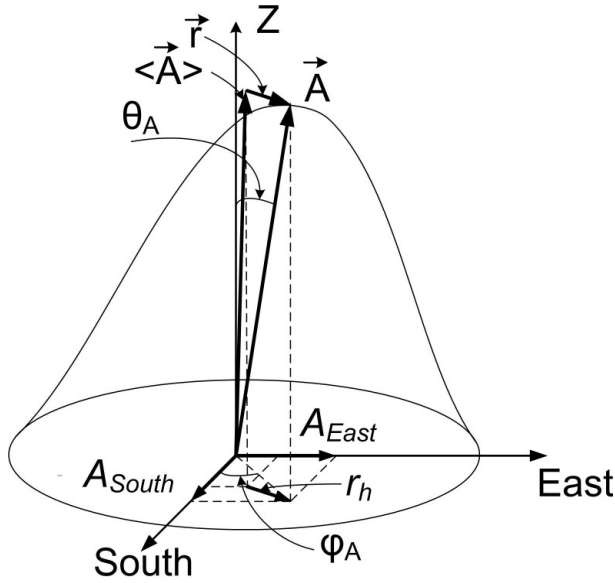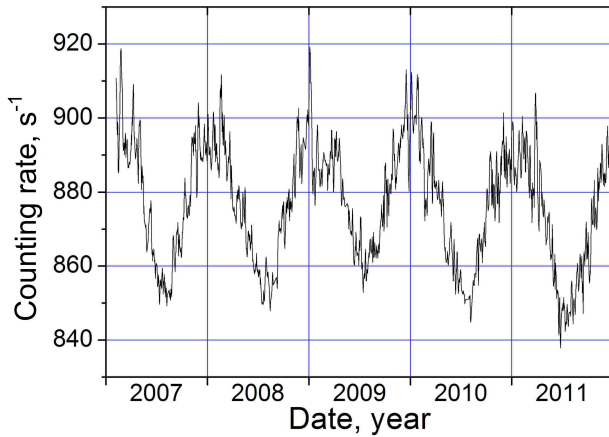
FIGURE 2. Vector of local anisotropy.



FIGURE 3. Time dependence of the daily average muon counting rate (for zenith angle interval $25° \div 76°$) estimated by the URAGAN data (normalized to one module).
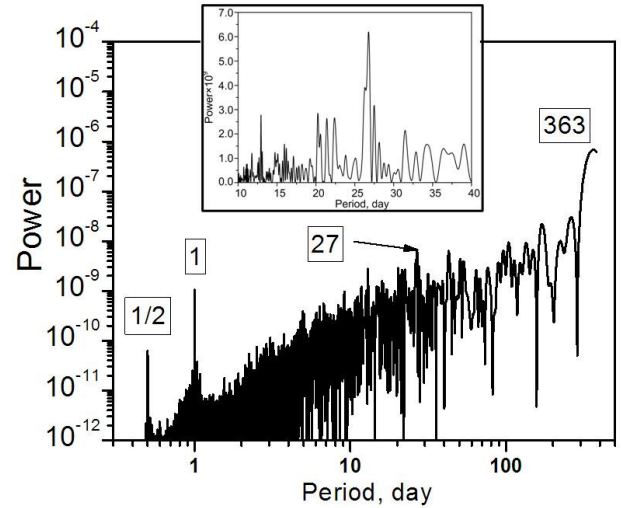


FIGURE 4. Fourier power spectra of the time series of the muon counting rate. In the boxes, the values of the periods (in days) are specified for the corresponding peaks.
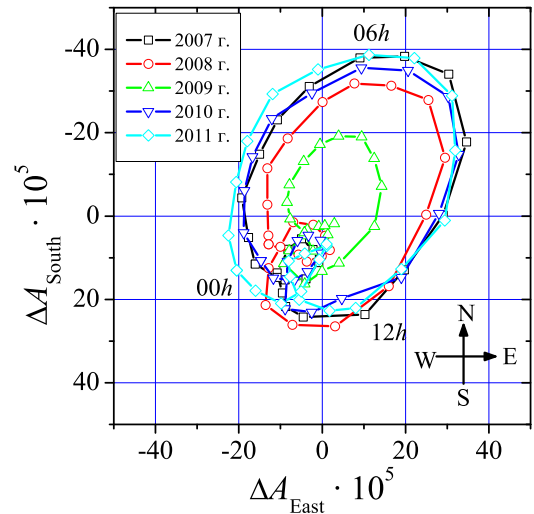


FIGURE 5. Correlations in the annual average diurnal cycle.

the integral counting rate, summed over three SMs (average 10-minute data corrected for barometric and temperature effects), and the counting rates for five zenith-angular ranges: $0° \div 17°$, $17° \div 26°$, $26° \div 34°$, $34° \div 44°$, and over $44°$, the boundaries of which were chosen to provide nearly equal statistics. The threshold muon energies depend on the zenith angle, and vary from 200 to 400 MeV. The FDs detected with the URAGAN hodoscope between 2006 and 2011 with amplitude of the decrease in the integral counting rate $\geq 0.5\,\%$ were selected. Figure 6 presents the results of a study of variations of muons and neutrons (from Moscow neutron monitor – MNM – data) during the Forbush decrease of July 11, 2011. Solar wind and IMF parameters are also shown.

The right panel of the figure presents GSE-images obtained for the moments of the maximum increase of $r_h$ during the period July 07–14, 2011. To obtain a GSE-image, a "muon snapshot" is projected on to

a magnetopause using asymptotic directions, and is transformed into the GSE (geocentric solar ecliptic) coordinate system [6]: $x$ is directed from the Earth to the Sun, $y$ is directed in the plane of the ecliptic against the movement of the Earth, and $z$ is parallel to the direction to the pole of the ecliptic. GSE is usually used to display the trajectories of satellites, observations of the interplanetary magnetic field and the solar wind.

## 4. CONCLUSIONS

The use of cosmic rays as a penetrating component in the heliosphere and muon hodoscopes as apparatus for formation of "muon images" of the magnetosphere and extra-terrestrial space opens a new approach for
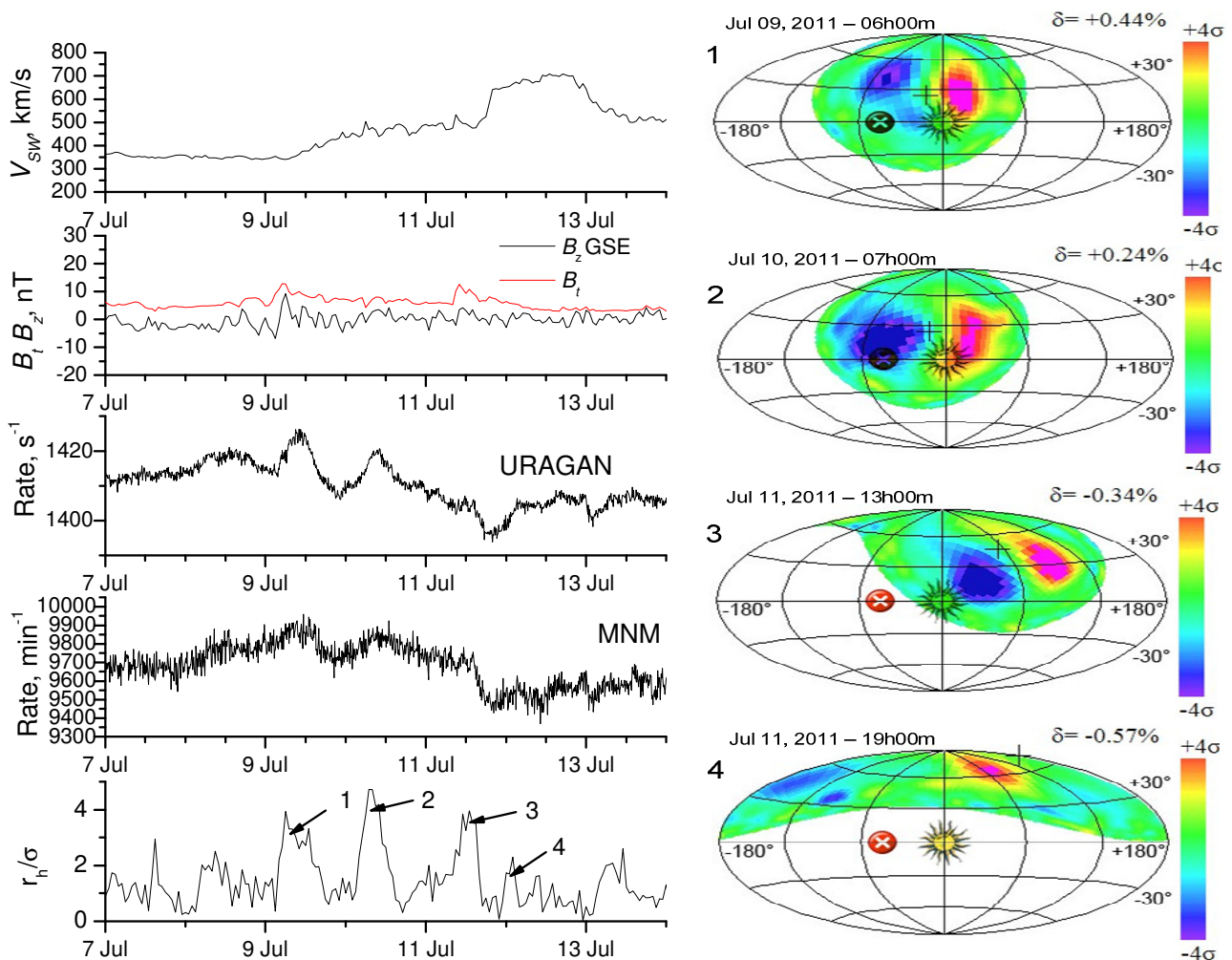
Figure 6. Variations of CR muons during FD of July 11, 2011. *Left (from top to bottom)*: solar wind velocity; parameters of the vector of IMF ($B_t$ and $B_z$); counting rate of the URAGAN; counting rate of the MNM; changes of $r_h$. *Right*: GSE-images obtained for moments indicated on the $r_h$ plot in the left panel. Note the behavior of the local anisotropy parameter $r_h$. Increasing $r_h$ (up to $4\sigma$ level) started 2 days before the beginning of FD. The cross in the circle indicates the direction of the interplanetary magnetic field force line.

remote monitoring of the environment. The analysis of muon flux anisotropy during heliosphere perturbations related with solar activity by means of even a single wide-aperture hodoscope provides a way to obtain unique information about the structure and dynamics of such events and to compare predictions of various models of heliospheric processes with direct measurements of muon flux variations.

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