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Local anisotropy of muon flux – The basis of the method of muon diagnostics of extra-terrestrial space

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Abstract

A new method for the analysis of spatial and angular characteristics of the cosmic ray muon flux registered in the hodoscopic mode using a single setup – the muon hodoscope – is presented. Various parameters of the muon flux anisotropy and methods of calculation of these parameters are discussed. It is shown that the horizontal projection of the muon flux relative anisotropy vector which characterizes lateral (horizontal) displacement of the muon flux angular distribution is the sensitive parameter to a variety of nonstationary processes in the heliosphere. The experimental data on the variation of the muon flux anisotropy during the passage of various irregularities in the solar wind and interplanetary magnetic field in the Earth's vicinity are presented.

Keywords: Cosmic rays; Muon flux; Local anisotropy; Muon hodoscope; Heliospheric disturbances

1. Introduction

Cosmic rays have been long and successfully used to study dynamic processes in the heliosphere. At the present time, the world-wide net of neutron monitors is used for this goal (Moraal et al., 2000). Another approach is connected with the detection of cosmic ray muons which have two main advantages. Firstly, in comparison with the neutrons, the muons are generated by primary particles with higher energies. Secondly, at high energies ($E > 10$ GeV) the muons keep the parent primary particle directions with a good accuracy (in average about 1–2° depending on the particle energy). In principle, this allows reconstruct the anisotropy of the primary cosmic rays distribution, related with the heliospheric events, with a good spatial and angular accuracy taking into account the geomagnetic field and the interplanetary magnetic field (IMF). But unfortunately most of the muon telescopes have not a good angular resolution (about 10°). The formation of the Global Muon Detector Network (GMDN) (Rockenbach et al., 2014) has improved the situation and allowed to solve this task using the same approaches to the data analysis as in the neutron monitor network. But overlapping of various zenith and azimuthal angle intervals in the selected directions: V, W, E, etc. (Yasue et al., 2003) – complicates the detailed description of heliospheric events.

New opportunities for such studies have been opened after the creation of a new type of detector – muon hodoscope for ground level registration of spatial-angular characteristics of the muon flux. The first muon hodoscope TEMP (angular accuracy 2°) was constructed in 1995 (Borog et al., 1995) and later a new approach to muon flux investigations based on the analysis of the two-dimensional angular matrices was proposed (Borog et al., 1997). A similar approach was realized in the narrow angle muon

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telescope at the Mt. Norikura (Ohashi et al., 1997), but its angular accuracy was worse (about 7°). The advanced muon hodoscope URAGAN with a large area (46 m^2) and angular accuracy better than 1° was constructed in 2006 (Barbashina et al., 2008).

URAGAN is a wide-aperture setup of a modular type, consisting of four separate supermodules (SM). The supermodule detects muons with a high spatial and angular accuracy (1 cm and 1°, respectively) over a wide range of zenith angles (0–80°). Hodoscope is located in the National Research Nuclear University MEPhI (Moscow Engineering Physics Institute) (Moscow, Russia) and is the part of the NEVOD setup.

The set of experimental methods of remote monitoring, based on the simultaneous registration of the muon flux from all directions of the celestial hemisphere in order to study various dynamic processes in the heliosphere, magnetosphere and the atmosphere of the Earth, constitute a new experimental discipline – the muon diagnostics.

2. Local anisotropy of the muon flux

Experimental data accumulated by the supermodules of the URAGAN setup equipped with a multi-channel measuring system are binary files that contain information about one-minute frames, which are formed by the control program during the setup operation.

The supermodule response represents the information about triggered strips in each of two projection planes XZ and YZ. Supermodules are oriented such that the X and Y axes are turned clockwise by 35° relative to the South and East geographical axes. Example of the event corresponding to the passage of a single muon registered by a supermodule is shown in Fig. 1.

Track parameters (zenith and azimuth angles or two projections of zenith angle) are reconstructed in real-time mode by the software based on histogramming the hits in each projection plane and accumulated in two-dimensional array during one-minute interval. The reconstruction of the track of each muon is the main distinction of the muon hodoscope from even narrow angular multidirectional muon telescopes which detect muons in fixed cells. In Fig. 2 an array (a matrix of muon arrival directions) for two projections of zenith angle (θ_X, θ_Y) is shown. It is a "muon snapshot" of the upper hemisphere, bounded by the aperture of the detector.

Features of zenith-azimuthal distribution of muon flux for some time interval can be characterized quantitatively by the parameters of the vector of local anisotropy $\vec{A}$,

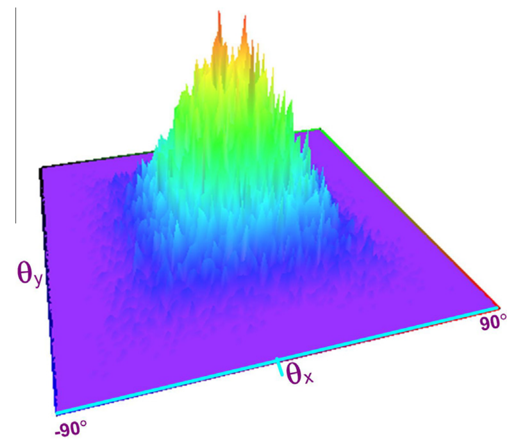

Fig. 2. One-minute data matrix.

which is the sum of the unit vectors with directions obtained in the reconstruction of single muon tracks, normalized by the number of events. Summarized vector indicates the average direction of the muon flux and is shown in local coordinates in Fig. 3.

Zenith-azimuthal distribution of directions of muon tracks in the URAGAN setup is formed in three types of matrices with different sizes of angular cells. The matrix with cell size 1° in zenith (θ) and 4° in azimuth (φ) angles is the most convenient for vector $\vec{A}$ calculation. The projections of the anisotropy vector in the local coordinate system of the detector in this case are calculated as follows (Shutenko et al., 2009, 2013):

$$A_X(t) = \frac{1}{N_0(t,\Delta t)} \sum_{\theta,\varphi} N_0(\theta,\varphi,t,\Delta t) \cdot \cos\varphi \cdot \sin\theta, \quad (1)$$

$$A_Y(t) = \frac{1}{N_0(t,\Delta t)} \sum_{\theta,\varphi} N_0(\theta,\varphi,t,\Delta t) \cdot \sin\varphi \cdot \sin\theta,$$

$$A_Z(t) = \frac{1}{N(t,\Delta t)} \sum_{\theta,\varphi} N(\theta,\varphi,t,\Delta t) \cdot \cos\theta,$$

$$N_0(t,\Delta t) = \sum_{\theta,\varphi} N_0(\theta,\varphi,t,\Delta t), N(t,\Delta t) = \sum_{\theta,\varphi} N(\theta,\varphi,t,\Delta t),$$

where: $N_0(\theta,\varphi,t,\Delta t)$ is the initial experimental value in the matrix cell; $N(\theta,\varphi,t,\Delta t)$ is the value in the matrix cell corrected for barometric effect; θ, φ are the middles of angular ranges of the cell; t is the start time of the matrix accumulation; Δt is the time interval of summation. In present work, we use $\Delta t = 1$ h, summation over azimuth (0–360°) and zenith (0–75°) angles determined by the detector aperture. The difference in the formulas used to calculate the

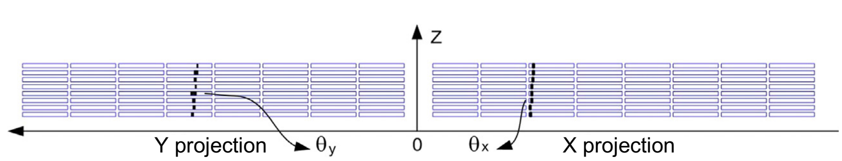

Fig. 1. The response of the supermodule of the hodoscope on the passage of a single muon.