Investigation of local deformations of muon flux angular distribution during CME with GSE-mapping technique

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Abstract. Coronal mass ejections (CME) have an impact on the flux of cosmic rays that penetrate the disturbed areas in the heliosphere and the near-terrestrial space. Unlike most ground-based cosmic ray detectors, the URAGAN muon hodoscope (MEPhI) allows to investigate both the integrated counting rate of registered particles and angular characteristics of the muon flux at the ground level. To select the local areas with statistically significant intensity changes, the angular distributions for the last hour and preceding it 24 hours corrected for the barometric effect are used. Angular distributions are smoothed, and the matrix of relative changes of the angular distribution in units of statistical errors is formed. The use of asymptotic directions calculated in advance, the angular cells of the matrix are mapped from the local coordinate system to the GSE coordinate system. The results of the study of GSE-mapping of local deformations of the angular distributions for different types of CMEs are discussed.

1. Introduction

The URAGAN muon hodoscope is the part of the Unique Scientific Facility “Experimental complex NEVOD” (MEPhI, Moscow). It is intended for the detection of the angular distribution of muons in a wide range of zenith angles and allows to obtain information about the variations both in the intensity and angular characteristics of the muon flux related with active processes in the heliosphere, the magnetosphere and atmosphere of the Earth [1]. Muons are generated in decays of pions which are produced in the interactions of primary cosmic rays (CR) with the nuclei of the atoms of the atmosphere, and keep quite well the directions of parent particles. Therefore, the study of variations of the angular distribution of the muon flux measured in real time mode allows to study the variations of primary cosmic rays caused by different phenomena associated with solar activity, including coronal mass ejections (CME). This is the basis of a new method for studying the surrounding space – muon diagnostics [2, 3].

URAGAN consists of four independent supermodules (SM). Each SM is assembled of eight layers of gas-discharge chambers (streamer tubes) equipped with two-coordinate system of external readout strips which provides a high spatial and angular accuracy of muon track detection (correspondingly, 1 cm and 1°) in a wide range of zenith (0° - 80°) and azimuthal (0° - 360°) angles in the real time
mode. Data are accumulated by minute intervals and contain matrices of two-dimensional angular distribution of the muon flux \([4, 5]\).

In this paper, it is proposed to use for the analysis of coronal mass ejections a new tool based on the analysis of muonographs obtained using the URAGAN muon hodoscope, specifically the analysis of deformations of the angular distribution in the GSE (Geocentric Solar Ecliptic) system.

2. Experimental data format

Data of each SM represent a sequence of 2D-muon intensity matrices (frames) of tracks of muons arriving from any direction of upper hemisphere collected during one minute intervals, detected and reconstructed in real time mode. One minute matrix contains \(\sim 80,000\) muons. For the analysis of long-time heliospheric disturbances, the sequence of one hour matrices averaged over the data of three supermodules obtained during one hour exposure is analyzed. The statistical reliability of every such matrix is about 15 million events. In figure 1 (left), a graphical representation (muonograph) of the matrix of changes of the angular distribution of events during last hour (the current matrix) with respect to the normalization matrix for the preceding 24 h is presented.

![Figure 1](image.png)

**Figure 1.** Muonographs of one-hour matrix in the laboratory system (left) and in the GSE coordinate system (right). The outer circle limits cells with zenith angles 75°. Inner circles correspond to zenith angles 30°, 45° and 60°.

For each angular cell of the matrix, asymptotic directions of primary particles for a given direction of the muon track in the detector were calculated \([6]\). Using asymptotic directions, the angular coordinates of the cells of the matrix changes are mapped from the laboratory system to the Geocentric Solar Ecliptic coordinate system. One of GSE images of 60-min matrix is shown in figure 1 (right). The figure also shows: the relative change in the counting rate \((\delta)\), the direction of the line of force of the interplanetary magnetic field (indicated by a circle with a diagonal cross), the direction to the Sun (the image of the solar corona) and asymptotic direction for vertical muons (cross) \([4]\).

3. GSE-mapping

On the GSE muonographs, regions are selected with deviation \(|\delta| > 3\sigma\). These areas are referred to as deformation areas. For each deformation area following values are calculated: solid angle in the GSE system, GSE-latitude and the GSE-longitude of the peak deviation value and its value in units of statistical error, peak value in percentages and its angular coordinates \((\theta, \phi)\) in the Laboratory Coordinate System. Time series of the characteristics of the selected deformation areas are preserved. These series are used to plot the GSE longitude directions of the peak values \((\theta, \phi)\) versus time. Size
of the points on the graphs depends on the size of the solid angle of the area, and the color – on the value of the peak value of the deviation inside the area. On the graphs, only areas with a solid angle larger than 0.02 sr are displayed. On the graphs with GSE-longitude, only areas with GSE-latitude less than 80° are displayed. In figure 2, the GSE-mapping of the matrix of changes in the particle flux is presented.

![GSE-mapping of the matrix of changes in the particle flux](image)

**Figure 2.** GSE-mappings of the matrix of particle flux changes with the correction of the angular distribution. Left: the original matrix; right: an image with selected regions of deformations.

Figure 3 shows examples of GSE longitudes of the deformation areas found by the matrix of changes of the angular distribution from August 15 to 25, 2017. Point size reflects the size of the selected area. Color indicates the level of variation.

![Examples of selection of areas in muonographs](image)

**Figure 3.** Examples of the selection of areas of low and high intensity in muonographs in the GSE system.

4. Observation of CME using GSE-mapping

Figure 4 shows GSE-mapping and changes in the Kp index during the coronal mass ejection, occurred on March 7, 2008. According to the CACTus database [7], the velocity this event was 766 km/s. The vertical red line shows the start time of the ejection. A day after the start of the CME, a magnetic perturbation with Kp = 4 was observed on the Earth, which later turned into a storm with Kp = 6. Compared with the preceding period (March 5–6, 2008), during the magnetic storm a characteristic increase in the deformation areas of the muonographs in the GSE system is observed. During these
events, an increase in the intensity of the particle flux by more than 3σ is observed with an angular cell size of more than 0.5 sr from the direction of the Sun at longitudes of 0 ° - 90 °.

Figure 4. The sequence of deformations of the angular distribution for muonographs in the GSE system and Kp-index in the period from March 5 to 19, 2008.

Figure 5 presents a similar GSE mapping and Kp-index for CMEs that occurred on 26 and 30 September 2009.

Figure 5. The sequence of deformations of the angular distribution for muonographs in the GSE system and Kp-index in the period from September 20 to October 10, 2009.
According to the CACTus database [7], velocities these events were 1578 km/s and 1838 km/s, correspondingly. Disturbances in the Earth magnetosphere were not observed. Kp-index after CMEs was less than 3. The number of areas where regions with deviation $|d| > 3\sigma$ increased compared with the period before the start. However, no selected angular directions in the GSE muonographs are observed.

Thus, we have observed different effects for ejections which affected and did not affect the near-Earth space. Using this effect based on the analysis of local deformations of muon flux angular distribution it is possible to separate events that cause disturbances in near-Earth space.

5. Conclusion
Using the muon hodoscope URAGAN, it is possible to track the modulations not only of the integrated intensity of the muon flux and the integral characteristics of the anisotropy vector, but also to analyze in time the changes in the angular distribution of the muon flux caused by the effects of inhomogeneities of the interplanetary magnetic field on the flux of charged primary cosmic rays.

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