Study of disturbances in the IMF and magnetosphere of the Earth by muon hodoscope data

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Abstract: Disturbances of interplanetary magnetic field (IMF) and of geomagnetic field caused by the solar activity significantly influence characteristics of cosmic ray flux – intensity and anisotropy. Variations of cosmic rays are being investigated more than 60 years, but these investigations were directed mainly on the study of changes of cosmic ray flux. The situation changed recently with the appearance of a new type of ground detectors – muon hodoscopes – which allow to register spatial-angular variations of the flux of the penetrating component of cosmic rays at a new level of precision and reliability. Possibilities of muon hodoscopes have allowed for the first time consider cosmic rays not only as an investigated object, but also as a tool for examination of the state of the near-Earth space. The URAGAN hodoscope with the area of ~ 45 sq.m located at the ground surface allows to use for such studies the hard component of cosmic rays (muons). URAGAN has a high angular resolution (~1°) in a wide range of zenith angles (0-80°) at registering tracks of charged particles, that gives possibility to explore the dynamics of angular dependences of the muon flux caused by various external factors. In this paper, results of the study of angular variations of muon flux by the URAGAN data of 2009-2011 during disturbances in the IMF and in the Earth’s magnetosphere are presented. It is shown that there is an interrelation between variations of IMF components, of solar wind parameters, and of anisotropy of muon flux. Changes of angular variation characteristics of muon flux sometimes can be observed several hours and even days before the moment of the beginning of the geomagnetic disturbance.

Keywords: cosmic rays, muon flux, interplanetary magnetic field, magnetosphere.

1 Introduction

At present, forecasting of geomagnetic disturbances is carried out by means of various methods based on a comparison of conditions of the surface and the crown of the Sun with characteristics of the interplanetary magnetic field (IMF) near the Earth. Sources of IMF disturbances can be heterogeneities of magnetic field on the Sun surface (coronal holes, active regions, sunspots) and coronal mass ejections. Propagation of IMF disturbances from the Sun to the circum-terrestrial space lasts from one to three days. It allows, having analyzed the data of solar observations (in optical and X-ray spectra), to draw conclusions on the degree of the future influence of IMF disturbances on the Earth magnetosphere. Since the propagation of disturbances from the Sun to the orbit of the Earth is based on model calculations, it is not sufficiently well predictable, whether the disturbance will reach the Earth magnetosphere and how it will affect it.

Direct observations of conditions in interplanetary space (IMF and solar wind) are carried out by space vehicles located now, basically, near the Earth. The quiet solar wind (~ 400 km s⁻¹ velocity) passes from a distant satellite ACE (~ 1.5 million km) to the Earth for about one hour. Thus, existing methods of forecasting of geomagnetic disturbances have not more than one hour for refinement of the forecast. Among the most advanced indirect methods of monitoring conditions in the heliosphere, it is possible to mark the search for interplanetary scintillations of astronomical radio sources (e.g., quasars) due to fluctuations of interplanetary plasma. In work by Bisi et al. (2010) [1] an example of a complex study of propagation of coronal mass ejection of 13 May 2005, which caused a powerful geomagnetic storm, from the Sun to the Earth is described.

Intensity of cosmic rays (CR) on the surface of the Earth depends on conditions of interplanetary space, magnetosphere and atmosphere of the Earth. Heterogeneity of solar wind and magnetic fields on the way of cosmic rays can influence their intensity, energy and angular distributions. These changes of CR flux are observed by means of ground-based neutron and muon detectors. At a cor-
rect account of atmospheric effects and under condition of a quiet magnetosphere, it is possible to make conclusions about conditions in interplanetary space basing on observations of ground level variations of cosmic rays. Now, there exist two global networks of cosmic ray detectors \[2\] (neutron monitors and muon detectors) carrying out monitoring of interplanetary space.

The URAGAN hodoscope \[3\] represents a new class of muon detectors, allowing to detect muon flux with a high angular accuracy (~ 1°) in a wide range of zenith angles (0-80°) simultaneously from all azimuth directions. The analysis of angular variations of CR flux during disturbances in the IMF and the Earth magnetosphere for the period since January 2009 till March 2011 is presented.

2 Experimental data

For allocation of intervals of IMF disturbances before geomagnetic storms, hourly data of OMNI2 \[4\] have been used. IMF disturbances were estimated with solar wind-magnetosphere coupling functions by Wygant et al. \[5\], Perrault and Akasofu \[6\], Newell \[7\]) and solar wind control function by Borovsky \[8\].

The initial URAGAN data (55.7° N, 37.7° E, 173 m altitude a. s. l.) are one-minute matrices of muon counting rate in different directions of the celestial hemisphere. For the analysis of angular variations of CR flux in one-hour integrated URAGAN data, the horizontal projections of the vector of local anisotropy \( \overline{A} \) were calculated (Fig. 1):

\[
\overline{A}_{\text{South}}(t) = \frac{1}{N(t)} \sum_{\theta} \sum_{\varphi} N(\theta, \varphi, t) \cos \varphi \sin \theta \\
\overline{A}_{\text{East}}(t) = \frac{1}{N(t)} \sum_{\theta} \sum_{\varphi} N(\theta, \varphi, t) \sin \varphi \sin \theta
\]

where \( t \) is the time corresponding to the matrix accumulation, \( \theta \) and \( \varphi \) are the angles corresponding to the matrix cell midpoints (\( \varphi = 0° \) – direction to the South, \( \varphi = 90° \) – direction to the East), \( N(\theta, \varphi, t) \) is the number of recorded events in a corresponding matrix cell (\( \theta \), \( \varphi \)), and \( N(t) \) is the total number of events in the used angular range. Summation is done over all azimuth angles and over zenith angles from zero to 75°. It is necessary to note that projections \( \overline{A}_{\text{South}} \) and \( \overline{A}_{\text{East}} \) calculated by means of the formula (1) do not depend on barometric and temperature corrections (under condition of azimuth symmetry of atmospheric pressure and temperature in a zone of sensitivity of the URAGAN hodoscope, ~ 90 km radius), and \( N(t) \) is the normalizing factor (without barometric and temperature corrections).

3 Results

For the period since January 2009 till March 2011, 124 intervals of IMF disturbances have been selected: 35 - in 2009, 71 - in 2010, and 18 - from January till March 2011. In Fig. 2, dependence of monthly number of intervals of disturbances on time is presented. From February 2010, the growth of the number of such intervals caused by intensification of the solar activity is observed.
Fourier power spectra of time distributions of $A_{\text{South}}$ and $A_{\text{East}}$ exhibit semidiurnal, diurnal and about 27-day cycles (Fig. 4). Semidiurnal and diurnal periods are more pronounced in variations of projection $A_{\text{South}}$. The powers of cycles with periods of 27.46 and 26.12 day for $A_{\text{South}}$ somewhat exceed powers of cycles with period 28.16 day for $A_{\text{East}}$.

Increased daily fluctuations of $A_{\text{South}}$ and $A_{\text{East}}$ not related with IMF disturbances approaching the Earth, may be caused by propagation of strong disturbances in other areas of the heliosphere.

In Fig. 5, two samples of variations of $A_{\text{South}}$ and $A_{\text{East}}$ and IMF disturbances for the cases when variations in $A_{\text{South}}$ and $A_{\text{East}}$ were revealed two and three days before the observation of IMF disturbances in OMNI2 data are presented. In Fig. 5, right, it is seen that as the IMF disturbance approaches the Earth, diurnal fluctuations begin to dominate in variations of $A_{\text{South}}$ and $A_{\text{East}}$ and then, with the beginning of the geomagnetic disturbance, the semidiurnal fluctuations become dominating. In Fig. 6, plots of correlations between $A_{\text{East}}$ and $A_{\text{South}}$ for four days are shown: 28 January 2010 – the quiet day; 31 January 2010 and 26 February 2011 – the days with disturbances; 10 March 2011 – the day of the greatest variation of anisotropy of muon flux.

### 4 Conclusions

As a result of the performed analysis of the URAGAN data, it has been shown that there is a certain interrelation between variations of IMF components and anisotropy of muon flux. However, the direct relationship between muon anisotropy variations and IMF parameters has not been found. Changes of angular variation characteristics of muon flux sometimes can be observed several hours and even days before the moment of the beginning of the geomagnetic disturbance.

<table>
<thead>
<tr>
<th>Category</th>
<th>$A_{\text{South}}$</th>
<th>$A_{\text{East}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>not revealed</td>
<td>33</td>
<td>51</td>
</tr>
<tr>
<td>masked by daily fluctuations</td>
<td>26</td>
<td>14</td>
</tr>
<tr>
<td>Seen 3 days earlier</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Seen 2 days earlier</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Seen 1 day earlier</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>Seen on the same day</td>
<td>43</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 1. Summary table of revealing of muon flux disturbances in variations of horizontal projections of the vector of local anisotropy by URAGAN data compared to intervals of the IMF disturbances selected according to OMNI2 data from January 2009 till March 2011.
5 Acknowledgments

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References


Fig. 5. Variations of $A_{\text{East}}$ and $A_{\text{South}}$, coupling function by Wygant et al. [5] (Ewav), control function by Borovsky [8] (R) and Dst-index for two events: left - from 27 January till 4 February 2010; right - from 23 February till 3 March 2011.

Fig. 6. Plots of correlations between $A_{\text{East}}$ and $A_{\text{South}}$ during 24 hours: a) – a quiet day; b) and c) - days with disturbances; d) – the day of the greatest disturbance. Figures near the points specify the time (hour, UT). The points are connected by the lines sequentially in time.