Study of heliospheric disturbances on the basis of cosmic ray muon flux anisotropy

I I Astapov, N S Barbashina, A N Dmitrieva, Yu N Mishutina, A A Petrukhin, V V Shutenko, E I Yakovleva, I I Yashin
National Research Nuclear University MEPhI, Moscow, Russia
E-mail: II Astapov@mephi.ru

Abstract. The features of the study of heliospheric disturbances on the basis of ground level cosmic ray muon flux observations are discussed. The muon hodoscope URAGAN simultaneously detects muons from various directions of the celestial hemisphere. This allows us to analyze spatial-angular variations of muon flux during such events. Heliospheric disturbances that caused the changes of interplanetary magnetic field parameters measured by various space vehicles are considered. A special attention is paid to the analysis of the response of the muon hodoscope URAGAN for recent most powerful solar flares that occurred in March 2012. In accordance with the results of the study, methods of separating main heliospheric disturbances are proposed. The prognostic potential of the developed approaches to the study of heliospheric disturbances by means of the penetrating component of cosmic rays is evaluated.

1. Introduction

The influence of the solar activity on heliospheric and magnetospheric processes is studied with the use of various equipments placed on satellites as well as on the surface of the Earth. As a result of these studies, a vast experimental material has been accumulated and some of relationships between the processes occurring on the Sun and in the heliosphere and the magnetosphere of the Earth have been established. Application of cosmic rays for such studies is of a great importance since cosmic ray particles propagate with the speed close to the speed of light that far exceeds the rate of propagation of any heliospheric disturbances. The usage of the muon component generated by primary cosmic-ray particles for this purpose is of a special interest since muons maintain the direction of the primary particles. Muon hodoscope URAGAN [1] registers the flux of cosmic-ray muons on the surface of the Earth simultaneously from various directions that allows to carry out the spatial and angular measurements of cosmic ray modulation in near-Earth space and study the muon flux variation dynamics in a wide range of zenith and azimuth angles with a single device. This, in its turn, allows studying the anisotropy of the muon flux caused by various disturbances of the heliospheric origin, and anisotropy observations may provide additional information about the nature of these disturbances much earlier than these disturbances reach the space vehicles operating near the Earth.

This work is a continuation of the research initiated in 2007 [2], but the technique of the analysis has been significantly modified. Variations of the anisotropy of the muon flux during 2011 which is characterized by a considerable increase of the solar activity have been analyzed.
2. Equipment and experimental data
Muon hodoscope (MH) URAGAN, a wide-aperture coordinate-tracking detector, was constructed in the Scientific and Educational Centre NEVOD (MEPhI). Hodoscope is capable to detect muons simultaneously from all directions of the upper hemisphere and is used to study characteristics of muon flux variations as a function of spatial angle. URAGAN was launched in a permanent operation mode in 2005. At present, hodoscope consists of four identical supermodules (SM) with total area about 46 m$^2$, and total counting rate is about 5500 muons per second. Each SM is assembled of eight layers of gas-discharge chambers (streamer tubes) equipped with two-coordinate system of external readout strips and provides a high spatial and angular accuracy of muon track detection (correspondingly, 1 cm and 0.7°) in a wide range of zenith angles. Every minute, angular distribution of muons is recorded in a two-dimensional angular matrix, which represents a snapshot of the upper hemisphere with 1-minute exposition. About three million matrices containing unique information on spatial-angular variations of the muon flux were collected during the experiment.

For the study of the response of muon flux variations registered by MH URAGAN, the local anisotropy vector \( A \) (one of the main characteristics of the angular distribution of muon flux) which is the sum of unit vectors with directions of reconstructed tracks in separate events normalized to the total number of muons \[3\] was used. The local anisotropy vector \( A \) indicates the average arrival direction of muons and is close to vertical. For the study of its deviations from the average direction, a relative anisotropy vector that is the difference between the current value of the vector and the average anisotropy vector calculated over a long period of time is used: \( \mathbf{r} = \mathbf{A} - \langle \mathbf{A} \rangle \). The length of the horizontal projection of the relative anisotropy vector characterizes the "side influence" on the angular distribution of the muon flux and is given by: \( r_h = \sqrt{r_x^2 + r_y^2} \). For the convenience of comparison of different events, its value is expressed in units of the RMS deviation (\( \sigma \)).

3. The technique of the study of heliospheric disturbances
In order to identify the disturbances in the heliosphere and magnetosphere, the OMNI database \[4\] that contains the characteristics of the interplanetary space (interplanetary magnetic field – IMF, and solar wind) obtained by using satellites and data on the geomagnetic activity from ground-based magnetic observatories was used.

Selection of heliospheric disturbances is based on the analysis of the magnetic induction of the interplanetary magnetic field \( B \). A disturbance was considered as a period of time not less than 3h with a value of \( B \) greater than 7 nT. The maximum value of the magnetic induction \( B \) and its time were recorded. In addition, to increase the accuracy of the selection of the disturbances, the value of the solar wind velocity, the magnetic induction vector projection on Z axis (\( B_z \) in GSE system) and the Dst-index were analyzed. For each of such disturbances of the interplanetary magnetic field the changes in the behavior of horizontal projection of the vector of relative anisotropy \( r_h \) were analyzed. The values which exceeded 2\( \sigma \) for at least 5 hour were considered as significant. The maximum values of the relative anisotropy vector were confronted with the maxima of the values of the IMF magnetic induction vector. It should be noted that, for a single disturbance in the IMF, the multiple response in muon flux anisotropy connected with the rotation of the Earth and, consequently, the changes in the direction of the muon hodoscope receiving cone can be observed. Therefore, several values of \( r_h \) could relate to a single event in the IMF (Figure 1).

For all events, the difference between the time of the maximum value of \( r_h \) and the time of the maximum value of \( B (\Delta t_{rh,B}) \) was calculated.
Figure 1. An example of the behavior of the magnetic induction of the interplanetary magnetic field (top) and horizontal projection of the relative anisotropy vector (bottom).

4. Results and discussion

In total, 202 disturbances of the IMF were selected in 2011. The increase of the anisotropy of the muon flux for the selected events was observed in ~75% of cases. Among them, 88% of these changes in the anisotropy of the muon flux were observed earlier than the changes in the behavior of the vector $B$. Figure 2 shows the distribution of the parameter $\Delta t_{rh-B}$ calculated for the events with the increase in anisotropy. Total statistics in the resulting distribution includes 150 events.

Resulting distribution (Figure 2) shows that the increase in the anisotropy of the muon flux appears, on the average, a day before the disturbance of the magnetic induction. In the distribution, three peaks with maxima at about -36, -24 and -12 are well seen.

Based on these results, the answer to the question “At what time of the day the anisotropy of the muon flux registered by MH URAGAN is mainly observed?” has been also given. Figure 3 shows the distribution of events with high values of $r_h$ in the time of the day. The largest number of periods with a maximum anisotropy of the muon flux is registered by muon hodoscope URAGAN from 4:00 UT to 12:00 UT. This time interval corresponds to the direction of the receiving cone of muon hodoscope towards the Sun.

Visual inspection of studied events revealed another interesting point. In those cases where the behavior of $B_z$ is regular ($B_z < 0$) the increase in the anisotropy of the muon flux is observed in
advance. But when the behavior of $B_z$ is turbulent (accompanied by one or more bursts with $B_z > 0$) the anisotropy of the muon flux varies almost simultaneously with the changes of $B_z$ and is greater in amplitude. This may indicate the dependence of the anisotropy of the muon flux on the type of heliospheric disturbance.

Let us consider in more details one of the heliospheric disturbances caused by the most powerful flare during the time of MH URAGAN operation (in March 2012). According to GOES data [5] there were three flares of X class at the beginning of March 2012: on March 5 with the maximum at 04:09 UT (X1.1); on March 7, the maximum at 00:24 UT (X5.4) and at 01:14 UT (X1.3). Figure 4 shows the variation of the magnetic induction $B$ and its projection $B_z$, solar wind velocity $V$, Dst-index and the anisotropy of the muon flux $r_h$ during this period.

Figure 4 shows that these flares caused strong disturbances in the heliosphere and magnetosphere. During the period, there are significant changes in the anisotropy of the muon flux that began almost simultaneously with the changes of the analyzed parameters. Maximum of $r_h$ reached a record value $7.2\sigma$ on March 8 at 13:00. However, the early appearance of the anisotropy of the muon flux in this event was not observed which is possibly related with a high velocity of propagation of disturbances in the heliosphere.

5. Conclusion
The approaches to the analysis of heliospheric phenomena using the parameters characterizing variations of muon flux described above illustrate a wide range of applications of this method. Deployment of a network of muon hodoscopes similar to the network of neutron monitors will allow creating a system for early detection of various phenomena in the heliosphere at any time of the day.

Acknowledgments
The work was performed in Scientific and Educational Centre NEVOD in frame of the leading scientific school NSh-6817.2012.2 with the support of Russian Ministry of Education and Science (contract no. 16.518.11.7053) and Federal Target Program "Scientific and pedagogical cadres for innovative Russia".

References
[1] Barbashina N S et al 2008 Instrum. Experim. Techniques. 51 180
[2] Timashkov D A et al 2009 Proc. of the 31st ICRC (Lodz) id891
[3] Shutenko V V et al 2009 Bull. Rus. Acad. Sci. Physics 73 347
[4] OMNI Database: ftp://nssdcftp.gsfc.nasa.gov/spacecraft_data/omni
[5] NOAA/SWPC: http://www.swpc.noaa.gov/today.html