Observation of heliospheric disturbances in muon component of cosmic rays at ground level

Dmitry A. Timashkov, Natalia S. Barbashina, Konstantin G. Kompaniets, Giampaolo Mannocchi, Anatoly A. Petrukhin, Oscar Saavedra, Victor V. Shutenko, Gian Carlo Trinchero and Igor I. Yashin

***Abstract*—Results of monitoring of heliospheric disturbances by means of ground-based muon hodoscope are presented. The approach is based on the fact that the disturbed regions in solar wind and in IMF modulate galactic cosmic rays and lead to changes of ground level muon intensity in given direction. To study such modulations the muon hodoscope URAGAN (MEPhI, Moscow) allowing to measure the muon flux variations from thousands of directions of the celestial hemisphere with a high statistics is used. Methods of projection of muon arrival directions to GSE coordinate system (taking into account geomagnetic field) which give a possibility to observe heliospheric perturbations at large distances from the Earth are described. The examples of observations of heliospheric disturbances in "muon window" are presented. Perspectives of the further use of muon hodoscopes are also discussed.**

1. Introduction

RAPID growth of space infrastructure, expansion of the use of satellite communications, actual and future space missions demand the solution of one of crucial problems as of present days as of a new solar cycle: prediction of space weather events with high level of reliability.

Nowadays this difficulty is solved by means of all-wave monitoring of the Sun (using both ground-based and space-craft detectors) and by measurements of heliospheric conditions at some points in vicinity of the Earth (ACE, WIND, etc.) or immediately in the Earth magnetosphere (GOES). Information about the space between the Mercury's and the Earth's orbits is very scarce and this zone is still *terra incognita*.

STEREO mission can improve this situation since it allows to view the inner heliosphere from other sides than from the Earth. But independent ways for validation and diversification of heliospheric data are needed as before. One of perspective ideas is the examination of ground level cosmic rays variations to develop new forecast technique.

D.A.Timashkov N.S.Barbashina, K.G.Kompaniets, A.A.Petrukhin, V.V.Shutenko, I.I.Yashin are with Moscow Engineering Physics Institute, Moscow, 115409, Russia (phone: 7-495-323-9040; fax: 7-495-324-8780; e-mail: datimashkov@ mephi.ru).

G.Mannocchi, G.Trinchero are with Istituto di Fisica dello Spazio Interplanetario - INAF, Turin, 10133, Italy.

O. Saavedra is with Universita degli Studi di Torino, Turin, 10125, Italy.

Usually, to detect secondary cosmic ray variations, the world-wide networks of neutron monitors or muon telescopes are used. New possibilities in this direction are opened by the use of muon hodoscopes. Unlike the neutron monitors, muon hodoscopes have higher counting rate, are sensitive to more energetic primary particles (up to hundreds GeV). Since muons (in contrast to neutrons) keep primary particle direction, the opportunity to measure the galactic cosmic ray variations from various directions appears. Moreover, muon hodoscope allows to detect muons simultaneously from any direction of upper hemisphere and to form "muon images" of disturbed regions.

This principle underlies the muon diagnostics: a new technique of remote monitoring based on the simultaneous detection of muon flux generated by high energy primary particles from various directions for the study of different dynamic processes in the heliosphere and near-terrestrial space [1–2].

In muon diagnostics, a natural source of penetrative radiation in the heliosphere—galactic cosmic rays which have a high level of constancy and isotropy—is used. To study heliospheric disturbances it remains to unroll a special "screen" which can detect cosmic rays in real time mode with sufficient angular resolution. Muon hodoscope URAGAN is a prototype of such a "screen" and gives a possibility to test this approach.

2. Setup Description and Data Processing

Description of detector URAGAN can be found elsewhere [3–5]. URAGAN setup satisfies the main requirements to muon hodoscopes. It contains several coordinate planes equipped with two-coordinate data readout system. Such structure provides angular accuracy of muon track reconstruction better than 1 degree and ensures a high level of stability of muon detection efficiency. Total area of URAGAN is equal to 34.5 m^2 (three supermodules) and is sufficient to provide a high statistics: more than two hundred thousands muons per minute.

The supermodule response contains information about muon track in each of the X- and Y-projections. These parameters (two projection zenith angles) are reconstructed in real time mode and are accumulated in 2D-directional arrays (zenith and azimuth angles, or pair of projection zenith angles); after that information about individual muon track is lost. Every minute these arrays are recorded on the hard disc.

Thus, the main format of muon hodoscope URAGAN data is two-dimensional muon angular matrix (array). Sequence of such matrices allows conduct the filming of the upper hemisphere in "muon light". To study muon flux fluctuations, for every cell of the angular matrix the average number of muons (estimated during preceding 24 hours and corrected for atmospheric pressure) is subtracted, and results are divided by standard deviations. Obtained data array is a “muon photograph” of the upper hemisphere with 1-minute exposure. Resolution of such muon images is determined by sizes of angular cells in URAGAN matrix data which is chosen 2°×2° (in two projected zenith angles). These values are more than three times more than accuracy of muon track reconstruction in hodoscope.

To compare angular muon flux variations at ground level with variations of galactic cosmic rays in the heliosphere it is necessary to calculate asymptotic directions for each angular cell of muon matrix. These directions depend on geomagnetic coordinates of the detector, threshold energies of the setup (which for the URAGAN vary from 200 up to 600 MeV for different zenith angles) and average energies of galactic cosmic rays which give main contribution to URAGAN counting rate at given zenith angle. Dependence of the average energy on zenith angle was obtained on the basis of CORSIKA simulation [6] and has a following form: $E_p = 63 \cdot \cos^{-1.08} \theta$.

The task of calculation of the asymptotic directions was solved using the method of simulation of reverse muon trajectories from the detector up to generation level, and further simulation of reverse proton trajectories from muon generation level to magnetopause. In simulation, the following models are used:

- Multilayer model of the Earth atmosphere NRLMSISE-00 [7] based on a number of experimental data (from rockets, weather sondes, space shuttles, weather stations). Advantage of this model is a good description of stationary atmosphere up to 1000 km.
- Models of the Earth magnetosphere developed by Tsyganenko: TS04 [8] and GEOPACK-2005 [9]. In the models, the parameters of solar wind and interplanetary magnetic field (IMF) as well as Dst-index are taken into account.

Simulation of the asymptotic directions was performed for each angular cell of muon matrix of URAGAN data taking into account muon and proton ionization and radiation energy losses in atmosphere. In Fig. 1, several asymptotic directions calculated for calm geomagnetic period are presented. It is seen from the figure that even a single muon hodoscope has the acceptance cone allowing to detect angular perturbations of primary cosmic rays in a considerable part of celestial hemisphere.

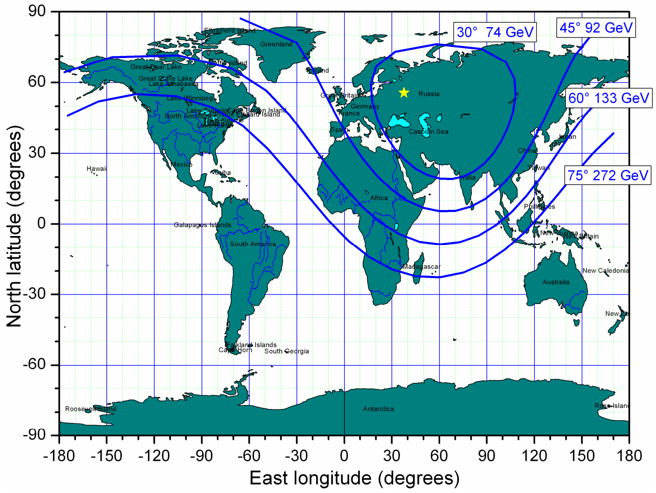

Figure 1. GEO projection of asymptotic directions of arrival of primary galactic protons. The star denotes the URAGAN location. Curves represent asymptotic directions for various azimuth angles at fixed zenith angles and average primary proton energies (labels near the curves).

3. Analysis of URAGAN data

Since February, 2007 three supermodules of URAGAN hodoscope are under operation. Total live time of monitoring exceeded 15 thousand hours, and about 800 thousands of one-minute muon snap-shots were recorded. Each muon matrix is corrected for atmospheric pressure using different coefficients for different zenith angles.

Capabilities of muon hodoscope to measure the angular dynamics of muon intensity with unexcelled angular resolution open a number of ways for analysis of muon flux variations during heliospheric disturbances. Here we consider only two: GSE-images and anisotropy vector.

A. GSE-images

To obtain GSE-image, a "muon photograph" is projected to magnetopause using asymptotic directions and is transformed into GSE coordinate system. In Fig. 2, one can see a sequence of GSE-images in "muon light". A scale at the figure denotes values of muon intensity changes in standard deviation units. To form these images only muons detected within the interval of zenith angles 0°–65° are used. Circle with X-sign denotes the direction to IMF line (average GSE longitude is equal to –45°). The Sun direction is pointed in the centers of images. A thin cross denotes the asymptotic direction for vertical muons at the ground level. Each image is obtained using one hour exposure.

In the Fig. 2, GSE-images during the period of magnetic cloud approaching the Earth are presented. The first image recorded at Nov 18, 00h (hereafter UTC) corresponds to calm conditions in the nearby heliosphere. Fluctuations of muon flux and consequently of primary galactic CR are insignificant (light yellow and green colors in GSE-image). But after several hours (Nov 18, 04h45m) muon hodoscope URAGAN detected a decrease region in the direction close to IMF line. Later, due to the Earth rotation the acceptance cone of muon hodoscope turned, and the effect disappeared. However, it was observed again the next night. In this case the decrease of muon flux intensity was detected earlier (Nov 19, 00h30m) and at passing IMF line direction (Nov 19, 05h) had a higher magnitude.

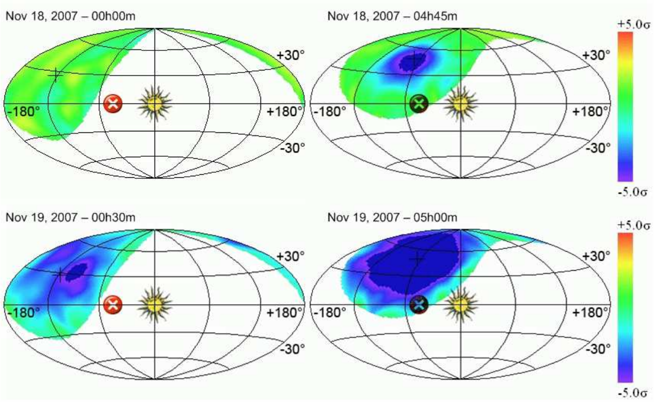

Figure 2. GSE-images of magnetic cloud approaching the Earth obtained by means of muon hodoscope URAGAN. Circle with X-sign denotes direction to IMF line; the Sun direction is pointed in centers of images.

The start of the disturbance in solar wind was detected by ACE [10] only at Nov 19, 17h UTC (Fig 3). Arrival of magnetic cloud itself was observed approximately at Nov 20, 01h. Thus, muon hodoscope URAGAN detected disturbances in muon flux caused by losses of primary protons along IMF direction (in loss cone) approximately 40 hours before the cloud arrival to the Earth.

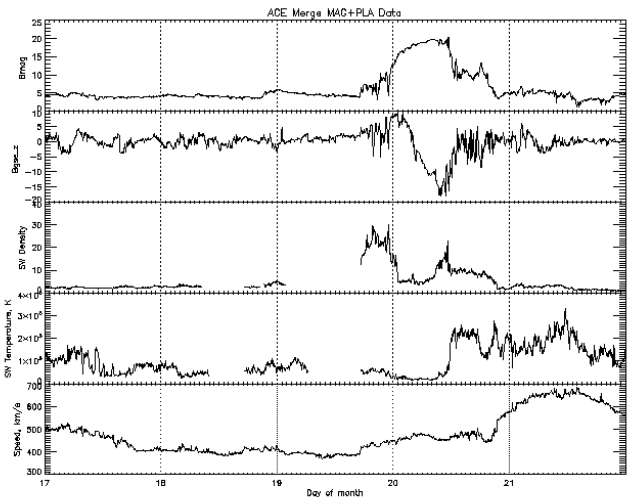

Figure 3. Solar wind and IMF parameters during passing of magnetic cloud on November 20 (data from ACE [10]).

Other examples of observation of heliospheric disturbances using GSE-image technique are shown in Fig.4. Here, two events concerned with passing of corotated interaction regions (CIR) are presented. Muon hodoscope URAGAN allows to observe the shape of disturbed regions. In the event of January 5, 2008 a loop-like structure is seen close to anti-Sun direction. In the event of March 9, 2008 a strange double object is detected: along with a region of deficit of particles, the region of excess is observed. It is interesting to note that these regions are symmetric relative to the Sun direction.

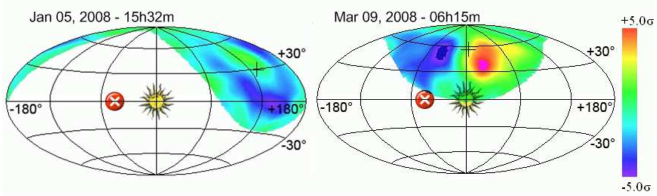

Figure 4. Examples of GSE-images obtained during passing of corotated interaction regions near the Earth on January 5 (on the left) and on March 9 (on the right) in 2008.

Although GSE-images provide yet only qualitative information, the use of GSE-images as input data may allow to solve an inverse problem and reconstruct the structure of interplanetary coronal mass ejections, magnetic clouds, CIRs and other heliospheric perturbations.

B. Anisotropy vector

Formation of GSE-images takes much time and has not yet been realized in on-line mode. For observation of heliosphere in real-time regime more simple characteristics of angular muon distribution may be used. In a general case muon flux intensity depends on both azimuth and zenith angle. Anisotropy vector describing preferred direction of muons arrival to ground level may be defined as the sum of unit vectors pointing the directions of arrival of each detected muon. Using the numbers of muons detected in each angular cell of muon matrix, the projections of the anisotropy vector can be written in a following form:

$$\begin{aligned} A_X(t) &= \frac{1}{M(t)}\sum_{\theta}\sum_{\varphi} N(\theta,\varphi,t)\cos\varphi\sin\theta\,, \\ A_Y(t) &= \frac{1}{M(t)}\sum_{\theta}\sum_{\varphi} N(\theta,\varphi,t)\sin\varphi\sin\theta\,, \\ A_Z(t) &= \frac{1}{M(t)}\sum_{\theta}\sum_{\varphi} N(\theta,\varphi,t)\cos\theta\,, \end{aligned} \tag{1}$$

where t is the time, θ and φ are centers of angular cells, $N(\theta, \varphi, t)$ is the number of muons detected within angular cell (θ, φ), $M(t)$ is the total number of detected muons. Summation is carried out from vertical direction up to maximum zenith angle over whole range of azimuth angles.

In Figure 5, time dependences of two projections of the anisotropy vector obtained from URAGAN data during March, 2008 as well as IMF and solar wind parameters from ACE [10] are presented. From the figure, the diurnal oscillations of the south (A_S) and the east (A_E) projections of anisotropy vector are clearly seen. During the period under consideration two heliospheric disturbances were detected: on March 9 and on March 25. Both times, a growth of magnitude of diurnal variations of the projections of anisotropy vector was observed. In the case of the second event, the effect in anisotropy vector appeared a day earlier than in ACE data.

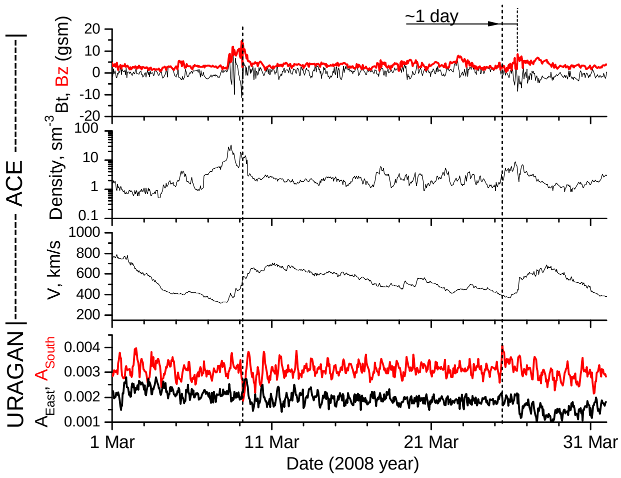

Figure 5. Behavior of the south and the east projections of the anisotropy vector from URAGAN as well as solar wind and IMF parameters [10] during March, 2008.

Thus, analysis of variations of the anisotropy vectors gives direct indications for the changes of equilibrium galactic cosmic ray flux caused by space weather processes.

4. Conclusion

Creation of a new type of ground level detector for studies of cosmic ray variations—muon hodoscope—and development of muon diagnostics methods open new possibilities of inner heliosphere monitoring by penetrative high energy particles. Even a single muon hodoscope is more informative than many standard muon telescopes and allows to form continuous series of “muon images” of the celestial hemisphere in a significant solid angle region with a high resolution. Data on muon variations can also be used for testing different models of evolution of heliospheric disturbances (e.g., coronal mass ejections and shocks).

No doubt, muon hodoscopes may significantly extend capabilities of existing ground level detector networks, and also be a basis of a new hodoscope network which will allow to conduct continuous monitoring of the heliosphere at a new level.

Acknowledgment

The research is performed at the Experimental Complex NEVOD with the support of the Federal Agency of Education, Federal Agency for Science and Innovations and RFBR grant (08-02-01204-a).

References

[1] N.S.Barbashina, V.V.Borog, A.N.Dmitrieva at el., "Muon diagnostics of tha Earth's atmosphere and magnetosphere", Bull. Rus. Acad. Sci., Phys., 2007, vol.71, no. 7, pp. 1041-1043.

[2] D.A.Timashkov, N.S.Barbashina, V.V.Borog et al., "Muon diagnostics of the Earth's atmosphere, near-terrestrial space and heliosphere: first results and perspectives", Proc. 30th ICRC, Merida, 2007, vol. 1, pp. 685–688 .

[3] D.V.Chernov, N.S.Barbashina, G.Mannocchi et al., Experimental setup for muon diagnosticsof the Earth's atmosphere and magnetosphere (the URAGAN project), Proc. 29th ICRC, Puna, 2005, vol. 2, pp. 457–460.

[4] N.S.Barbashina R.P.Kokoulin, K.G.Kompaniets et al., "The URAGAN wide-aperture large area muon hodoscope", Instr. Experim. Tech., 2008, vol. 51 no., 2, pp. 180–186.

[5] D.A.Timashkov, Yu.V.Balabin, N.S.Batbashina et al., "Ground level enhancement of December 13, 2006 observed by means of muon hodoscope", Astropart. Phys., 2008, vol. 30, pp. 117–123.

[6] E.I.Yakovleva, A.G.Bogdanov, A.N.Dmitrieva at al., "Coupling functions for primary cosmic rays and ground level muons at various zenith angles", 21st ECRS, Koshice, 2008, poster 4.05, to be published in this proceedings.

[7] http://modelweb.gsfc.nasa.gov/atmos/nrlmsise00.html

[8] http://geo.phys.spbu.ru/~tsyganenko/modeling.html

[9] http://modelweb.gsfc.nasa.gov/magnetos/data-based/Geopack_2005.html

[10] http://ftpbrowser.gsfc.nasa.gov/ace_merge.html