Muon diagnostics of the Earth's atmosphere, near-terrestrial space and heliosphere: first results and perspectives

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Abstract: Muon diagnostics is a new technique of remote monitoring of the development of various dynamic processes in the heliosphere and in the atmosphere and magnetosphere of the Earth based on the analysis of spatial-angular and temporal variations of muon flux simultaneously detected from all directions of the upper hemisphere. For practical realization of the technique, multi-directional muon detectors (hodoscopes) with large acceptance and high angular accuracy were designed and constructed in Moscow Engineering Physics Institute. First results of data analysis show that registration of muon flux in hodoscopic mode gives unique real-time information about processes in the Earth's atmosphere and also about phenomena in the interplanetary space related with solar activity. The use of muon diagnostics for remote localization of disturbed regions in the Earth's atmosphere and near-terrestrial space and its forecasting potential are also discussed.

Introduction

Despite of enormous amount of information related to our space environment the problem of space weather forecasting has not been solved. One of the main reasons of this fact is a scarcity of information about heliosphere conditions between the Mercury's and the Earth's orbits. Now all scientific resources either directly observe the Sun (Hinode, RHESSI, SOHO, etc.) as the main source of all space weather perturbations or are situated nearby the Earth: 1.5 million km (ACE) or closer (GOES).

The principally new possibilities are related with approaches directed to revealing heliospheric disturbances at large distances from the Earth: deployment of space-born systems far from the Earth or developing ground level cosmic ray detectors including those of new type.

A new era in solar space research started with the launch of the STEREO mission [1] last autumn. As to ground-based detectors: the world-wide net of neutron monitors and muon telescopes [2], systems of radiotelescopes for measurements of interplanetary scintillations [3] and new type of muon detectors (muon hodoscopes) are being now actively developed.

This article is devoted to description of principles of the use of wide-aperture muon hodoscopes for monitoring of the heliosphere, the Earth's magnetosphere and atmosphere and to discussion of first results and further perspectives of this approach.

Principles of muon diagnostics

The intensity of cosmic rays (CR) at ground level (mainly muons) varies under the impact of atmospheric conditions. Besides of these phenomena of a local character, there are global reasons of cosmic ray intensity modulations determined by geophysical cyclic processes and processes related with solar activity. Thus, muon flux variations bring information about both atmospheric and extra-atmospheric processes. Basic conceptions of the theory of such CR variations of atmospheric and extra-atmospheric origin were developed in the middle of XX century

[4–5]. Now, with the creation of wide-aperture muon hodoscopes with high angular resolution [6–7] the possibility to study inner structure and real-time dynamics of disturbances in the Earth's atmosphere and near-terrestrial space by means of cosmic ray muons registration is opened [8].

Movement through the heliosphere of magnetized plasma clouds formed as a result of coronal mass ejections (CME) causes the deflection of galactic CR (see Figure 1) and hence decrease the flux of muons generated in upper layers of the atmosphere and directed at plasma clouds. Thus, spatial-angular variations of muon flux can be used for localization of heliosphere disturbances and as a precursor of perturbation of the Earth's magnetosphere.

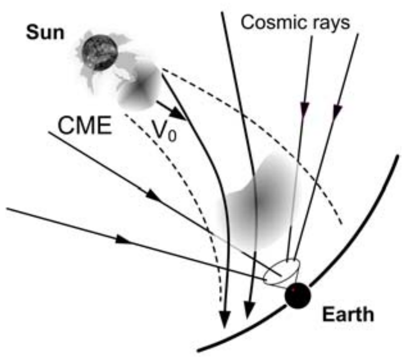

Figure 1: Deflection of galactic cosmic rays related with solar activity.

On the other hand, muon flux at the ground level is strongly related with different thermodynamic processes in the Earth's atmosphere at generation level (barometric, temperature effects) and with more complex wave processes in low stratosphere (inner gravitational waves of air density, significant density gradients, etc.) correlated with different turbulent and wave processes of geophysical origin, which are localized in space and time (see Figure 2). Wave processes at the altitude of muon generation modulate muon flux and can be used as precursor of origin and development of such phenomena at large distances from the muon detector.

The registration of spatial-angular dynamics of muon flux gives unique initial data for the developing of muon diagnostics – a new technique of remote monitoring and forecasting of dynamic processes in the heliosphere and in the magnetosphere and atmosphere of the Earth based on the analysis of variations of ground level muon flux simultaneously detected from all directions of the upper hemisphere in hodoscopic mode.

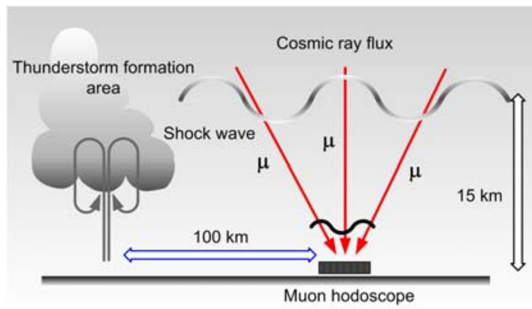

Figure 2: Modulations of cosmic ray muon flux in upper layers of the atmosphere.

Detector requirements

For the first time, cosmic ray variations during strong geomagnetic perturbations (Forbush decreases) were detected in muon flux [9]. The further study of cosmic ray variations at the Earth's surface was conducted mainly by means of neutron monitors, which can measure only integral flux. Traditional muon telescopes can detect the flux of atmospheric muons from one or several directions but do not have sufficient aperture and angular resolution to study spatial and temporal dynamics of muon flux.

In order to realize the principles of muon diagnostics, the wide-aperture muon hodoscopes, which give the possibility to simultaneously measure the intensity of muons from all directions of upper sky hemisphere, are necessary. Such detectors must have high angular resolution of muon track reconstruction (of the order of 1 degree) and large sensitive area to provide necessary statistical accuracy of experimental data for all zenith and azimuth angular bins (of the order of 10^6 events per hour). As total muon flux at the Earth's surface is about 0.01 cm $^{-2}$ s $^{-1}$, the area of ground level detector must be about 10 m^2 or larger. Since 1996 in Moscow Engineering Physics Institute the first muon hodoscope TEMP [6] is under operation.

The first supermodule (SM) of new muon hodoscope URAGAN [7] was launched in March,

2005. During test measurements, interesting results on muon variations accompanying Forbush decreases and strong atmospheric perturbations in Moscow region were obtained [8, 10]. The second SM was arranged in the beginning of 2006, and in April, 2006 the continuous measurements of muon flux from upper hemisphere by means of two URAGAN supermodules were started. In February 2007, the third SM was put into operation, and total area of hodoscope reached 34.5 m.

Monitoring of modulation processes related with solar activity

Muon hodoscopes give a possibility to conduct a muon-raying (by analogy with X-raying) of heliosphere disturbances using galactic high energy particles as penetrating radiation. Analysis of URAGAN data during Forbush effect allows investigate the dependence of muon flux decrease on various threshold energies and measure in "muon light" two-dimensional pictures of cosmic ray deflection by interplanetary CMEs [11]. During December 13, 2006 GLE event, 2D-dinamics of muon flux formed in the atmosphere by solar energetic protons for the fist time was measured by means of two URAGAN supermodules [12].

The possibility of tracing of disturbed regions by means of muon hodoscopes represents a special interest. On July 6 at 08:54 UT a big CME cloud was emitted from the Sun (from http://lasco-www.nrl.navy.mil/). This ejecta and shock wave in front of it crossed the Earth's orbit approximately 3.5 days later on July 9, about at 22:00 UT. At middle latitudes a classic sharp Forbush decrease was not registered and magnetic storm was not very strong (Kp = 4), that allows say that the ejecta passed apart from the Earth.

However, in muon hodoscope data a strong loss cone anisotropy was observed at nights July 7 – 8 and July 8 – 9 when hodoscope acceptance cone was directed at IMF line direction. In Figure 3, snap-shots of upper hemisphere in "muon light" are shown. These data were obtained at night of July 8 – 9 that is 20 hours before shock wave arrival to the Earth's orbit. In the figure the angular matrices of muon flux form the upper hemisphere in θx, θy plane are presented. To smooth Poisson fluctuations a special Fourier filter is used. Thin lines identify North-South and West-East directions. The deep blue regions correspond to a strong muon flux anisotropy caused by deflection of primary cosmic rays by CME propagated from the Sun.

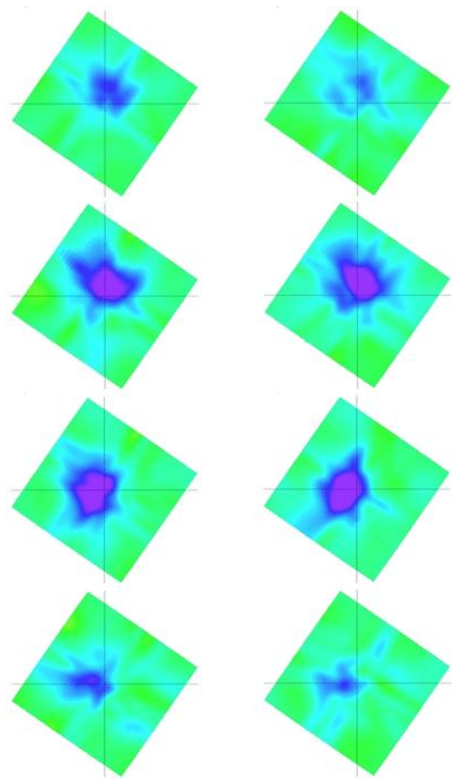

Figure 3: Muon snap-shots of CME at night July 8 - 9. From top: Jul 8 - 22h, Jul 9 - 00h, 06h, 08h. Each snap-shot corresponds to one hour exposure.

A shift of muon deficit region through the acceptance zone of muon hodoscope is clearly seen from comparison of 00h and 06h snap-shots. The same effect but of lower amplitude and during shorter time was registered at preceding night (July 7 – 8) that is 40 hours before CME arrival.

Monitoring of atmospheric processes

During the period of 23 – 27 June 2005, above the European part of Russia a powerful atmospheric front was moving from North-West. Results of wavelet analysis technique [10] of URAGAN data accumulated during this period are presented in Figure 4 for two ranges of frequencies. The existence of harmonic component with a period about 5.5 hours that appeared one day before the arrival of atmospheric front in Moscow is clearly seen in Figure 4 (top panel).

During 26 June, in the North of Moscow region a strong hurricane was generated by powerful turbulent processes at the atmospheric front. It appeared in Dubna town at 12:00 of local time. In Figure 4 (low panel), existence of two waves with periods about 95 and 70 minutes was found. These waves appeared several hours before the moment of hurricane arrival in Dubna (140 km from the setup), indicated in the picture by gray strip.

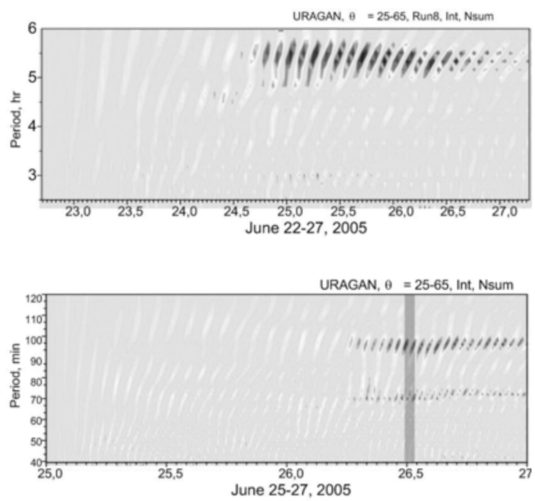

Figure 4: Wavelet-analysis of URAGAN muon flux variations in June, 2005. Top panel – for middle-period range; bottom panel – for short periods.

Conclusion

The use of cosmic rays, in particular of muons, as a penetrating component and muon hodoscopes as apparatus for detection of "muon images" of atmosphere and extra-terrestrial space opens new perspectives for remote monitoring of the environment. Registration of muon flux during heliosphere perturbations (like CME, magnetic clouds, solar energetic particles, and so on) using even a single wide-aperture hodoscope gives a possibility to obtain a unique information about the structure and dynamics of such events and to compare the predictions of various models of heliospheric processes with direct measurements of muon flux variations. The use in future of the world-wide net of muon hodoscopes may substantially widen the possibilities of ground-based space weather monitoring.

The use of muon hodoscopes for diagnostics of active phenomena in the Earth's atmosphere will give possibility to watch the inner atmospheric processes at principally new level and in future forecast dangerous phenomena of local character (tornados, sudden powerful hurricanes, etc.).

Acknowlegments

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 grants (06-02-08218-ofi and 06-02-17213-a).

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