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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 various dynamic processes in the heliosphere and in the magnetosphere and atmosphere 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 phenomena in the interplanetary space related with solar activity and also about processes in the Earth's atmosphere. The use of muon diagnostics for remote localization of disturbed regions in near-terrestrial space and in the Earth's atmosphere 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 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 and carry out the measurements nearby the Earth: 1.5 million km (ACE) or closer (GOES and others). New promising 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. An important step in this direction has been done with the launch of the STEREO mission [1] last autumn. However, along with the use of spacecrafts, as before the independent ground-level measurements are needed to explore high-energy solar particles and to develop approaches to remote monitoring of the heliosphere.

A special role in exploration of heliospheric processes is played by cosmic rays (CR). The flux of high-energy particles is practically constant in time and isotropic in directions, and thus its variations at ground level bring information about processes in heliosphere and in the Earth's magnetosphere and also about atmospheric condition. For the first time, cosmic ray variations during strong geomagnetic perturbations (Forbush decreases) were detected most likely in muon flux [2]. Nowadays, studies of cosmic ray variations at the Earth's surface are conducted mainly by means of neutron monitors. Basic conceptions of the theory of CR variations of atmospheric and extra-atmospheric origin were developed in the middle of XX century [3–4]. Now the worldwide net of standard ground-level detectors (neutron monitors and muon telescopes) and new analysis techniques of their data are used to study the heliospheric and magnetospheric perturbations [5]. However, single neutron monitor cannot give information about direction of particle arrival and standard muon telescopes have insufficient resolution for studies of spatial-angular muon flux dynamics.

Wide perspectives are opened with the use of new type of muon detectors—muon hodoscopes, which can simultaneously detect muons from the whole celestial hemisphere [6]. Muon flux variations are sensitive both to atmospheric and extra-atmospheric processes. Therefore, the use of high energy galactic cosmic rays and produced by them secondary muons as penetrating probes gives a possibility, by means of solution of inverse task, to explore not only the heliosphere and near-terrestrial space but also atmospheric processes. This paper is devoted to description of principles of the use of 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

Movement of magnetized plasma clouds formed as a result of coronal mass ejections (CME) through the heliosphere causes the deflection and losses of galactic CR (see Figure 1) and hence the 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.

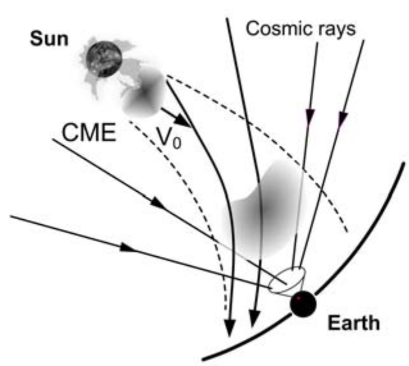

Figure 1: Deflection of galactic cosmic rays related with solar activity.

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.

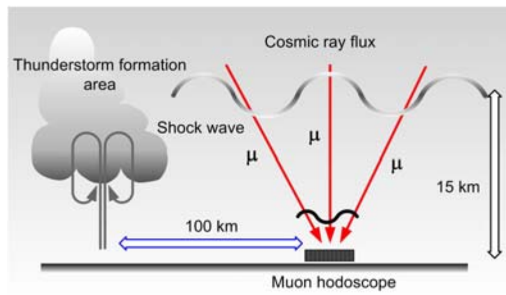

Figure 2: Modulation of cosmic ray muon flux in upper layers of the atmosphere.

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.

Detector requirements

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 two-coordinate data readout system to form 2D-images in "muon light", high angular resolution of muon track reconstruction (of the order of 1 degree) and large sensitive area to provide a good statistical accuracy of experimental data for all zenith and azimuth angular bins (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 [8–9]. The second SM was deployed in the beginning of 2006, and in April, 2006 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 to explore 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 and shocks [10]. During December 13, 2006 GLE event, for the fist time 2D-dynamics of muon flux formed in the atmosphere by solar energetic protons was measured in real-time mode by means of two URAGAN supermodules [11]. The possibility of tracing of disturbed regions by means of muon hodoscopes is of a special interest. On July 6, 2006 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 to 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 (see Figure 3). To smooth Poisson fluctuations the muon angular matrices after subtraction of average values and division by rms deviation for each directional cell have been processed with a special Fourier filter. After this, all directions were recalculated into GSE system on the basis of Tsyganenko model [12] and assumption that average primary proton energy for URAGAN's muons is equal to 40 GeV.

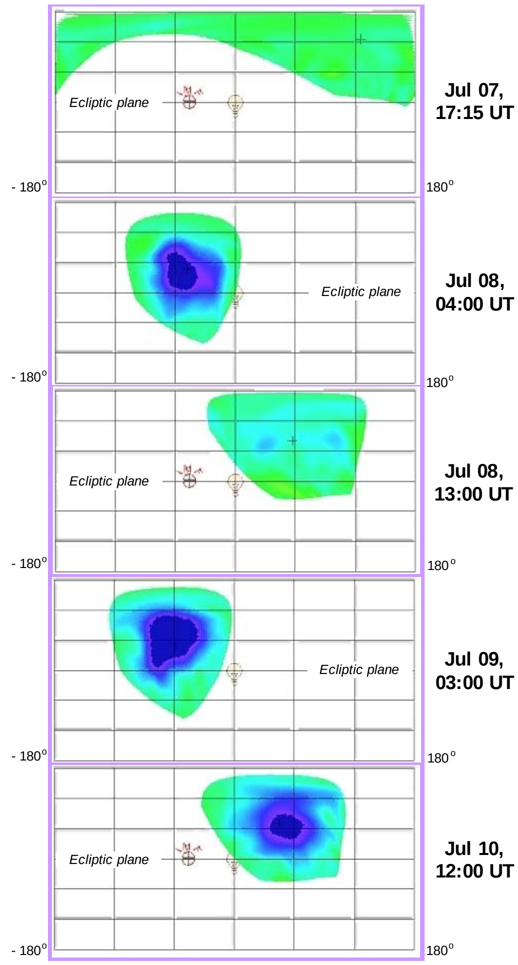

Figure 3: URAGAN muon windows during July 7–10 in GSE system. Abscissa is an azimuth angle (–180°, 180°), ordinate is the angle to ecliptic plane (–90°, 90°). The lamp denotes the Sun direction; from left of it the IMF direction is also shown. Each snap-shot corresponds to one-hour exposure, the times on the right indicate the middles of the exposures.

In the Figure, the first snapshot corresponds to quiet period when ICME and shock were far from the Earth. In the next snapshot one can see a significant decrease caused by losses of primary protons along IMF direction (in loss cone). It is remarkable that the effect was observed 40 hours before the shock arrival. Further, due to the Earth rotation, a calm snap-shot was seen in hodoscope view again. When hodoscope acceptance cone was directed to IMF line next time (Jul 9, 03h UT), loss-cone effect was observed more clearly; it was remaining about 20 hours till shock arrival. In the last snapshot, after shock passing through the Earth magnetosphere the decrease was observed in any (not only IMF) direction (Forbush zone).

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. 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, 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 a gray strip.

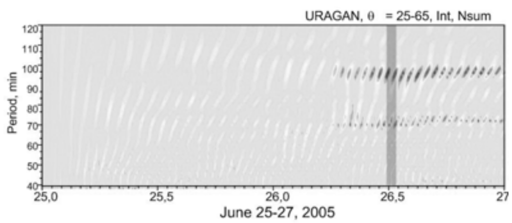

Figure 4: Wavelet-analysis of URAGAN muon flux variations in June, 2005.

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. Studies of muon flux variations allow to obtain information about high energy solar particles, above the neutron monitors rigidity range [13]. 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 unique information about the structure and dynamics of such events and to compare predictions of various models of heliospheric processes with direct measurements of muon flux variations. The use in future of the worldwide net of muon hodoscopes may substantially widen the possibilities of ground-based space weather monitoring. Besides, we hope that muon 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 to forecast dangerous phenomena of a local character (tornados, sudden powerful hurricanes, etc.).

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