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Muon Diagnostics of the Earth's Atmosphere and Magnetosphere

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Abstract—A method of distant monitoring of the Earth's magnetosphere and atmosphere is described, which is based on the close correlation between the modulations in the flux of atmospheric muons detected at the Earth's surface and the dynamic processes in the Earth's magnetosphere and atmosphere and implies the use of large-area muon hodoscopes with high angular accuracy of muon detection. The results of the analysis of the experimental data obtained on the muon hodoscopes used at the Moscow Engineering Physics Institute show that muon detection at the Earth's surface in the hodoscopic mode gives a qualitatively new information about the main sources of muon flux modulation.

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INTRODUCTION

Global changes in the planetary climate, accompanied by an increase in the number of hurricanes, waterspouts, tornadoes, and other catastrophic atmospheric phenomena (including those occurring in the previously quiet regions), stimulate development of systems for early detection of dangerous meteorological phenomena. This problem is urgent not only for the Earth's atmosphere but also for the circumterrestrial space because the satellite systems used for space weather monitoring do not perform remote scanning but are fixed either at the Lagrange point (ACE, SOHO) [1, 2] or at a certain circumterrestrial orbit (GOES) [3].

An independent line of investigation of the state of the Earth's heliosphere, magnetosphere, and atmosphere is based on measurements of cosmic-ray (CR) variations on the surface of the Earth. Development of a neutron monitor network and establishment of world data centers [4, 5] made it possible to analyze the CR variations recorded at different points of the terrestrial sphere and thus consider the planet Earth as a very large CR detector. However, the use of only neutron monitors for study of CR variations is obviously insufficient. Important information can be derived from measurements of the CR muon flux with muon telescopes, which make it possible to reconstruct the muon propagation direction. A new type of CR detectors are large-area muon hodoscopes, which can scan the entire celestial hemisphere in real time. Fabrication of the first muon hodoscope [6] was a starting point for development of muon diagnostics—a method of distant monitoring based on simultaneous detection of muon fluxes from different directions to study the dynamic processes in the circumterrestrial space and the Earth's atmosphere.

PHYSICAL BASES OF MUON DIAGNOSTICS

The principles of muon diagnostics can be illustrated by simple examples of modulation of fluxes of cosmic particles (primarily muons) at the Earth's surface in different, both atmospheric and extra-atmospheric processes.

Solar plasma clouds formed during coronal mass ejections may cause strong perturbations of the interplanetary magnetic field. The magnetic fields related to the cloud deflect primary CR particles and decrease the CR flux. In contrast to the Forbush decrease, which occurs when a solar plasma cloud completely encloses the Earth, a decrease in the muon flux in a specified direction (taking into account the magnetic force lines) can be detected when the cloud is located at a large distance from the Earth's orbit.

The physical essence of muon diagnostics of atmosphere is the close relationship between various atmospheric phenomena and the processes of production and transmission of muons in atmosphere. Along with the integrated modulation of the muon flux at the Earth's surface—barometric and temperature effects—there are more complex mechanisms of modulation of this flux. They are related to the propagation of different waves in the upper atmosphere, which are generated during formation of turbulent zones—nuclei of future waterspouts and hurricanes.

EXPERIMENTAL

CR modulation during strong magnetic perturbations (the Forbush effect) was detected for the first time specifically in muon fluxes [7]. Further study of CR variations at the Earth's surface was generally performed using neutron monitors, which measure inte-

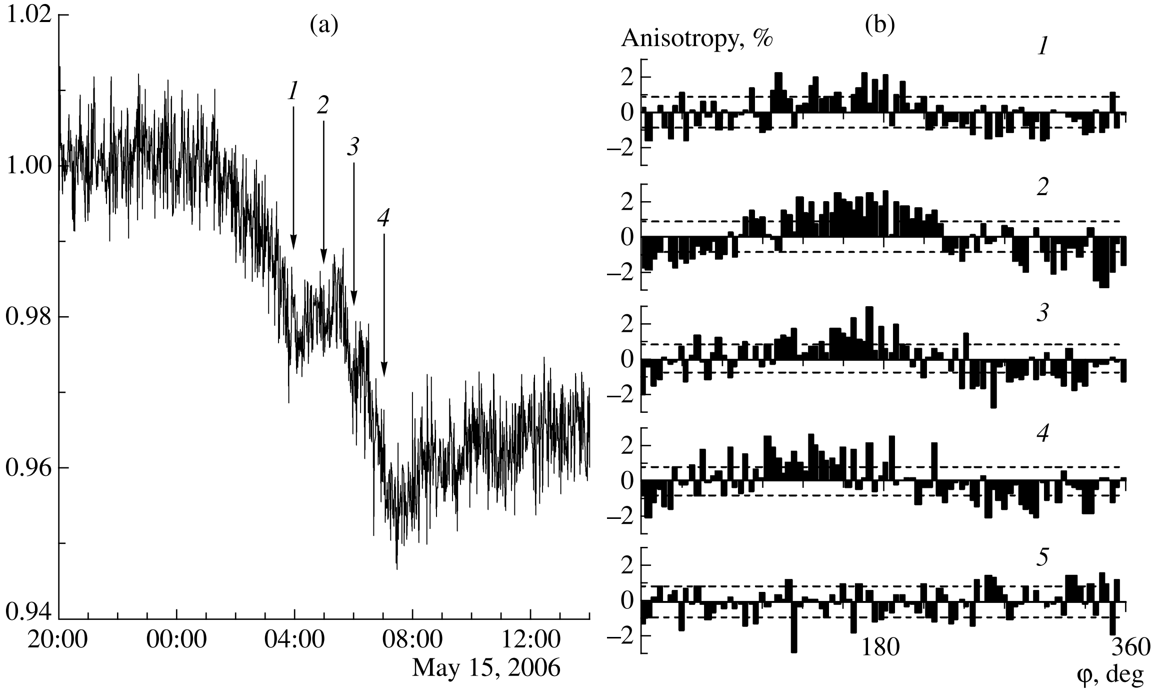

Fig. 1. (a) Change in the count rate of the URAGAN muon hodoscope during the event of May 15, 2005 and (b) the dynamics of relative azimuthal anisotropy of the muon flux for several instants in that period: (*1*) 4:00, (*2*) 5:00, (*3*) 6:00, and (*4*) 7:00 (UTC time) and (*5*) for quiet geomagnetic conditions.

grated fluxes. Muon telescopes can detect atmospheric-muon fluxes propagating in one or several directions but they lack a sufficiently high aperture ratio to investigate the spatial angular muon flux dynamics.

To scan the celestial hemisphere, it is necessary to use wide-aperture muon detector hodoscopes, which make it possible to measure simultaneously muon flux intensities in different directions. Such detectors must have a high angular accuracy of reconstruction of muon tracks (1° or better) and provide a sufficient statistical completeness of experimental data (at a level of several millions of events per hour). To this end, large-area systems are necessary. For example, for an integrated muon flux intensity at the Earth's surface of about 0.01 cm^{-2} s^{-1}, the detector area should be no less than 10 m^2.

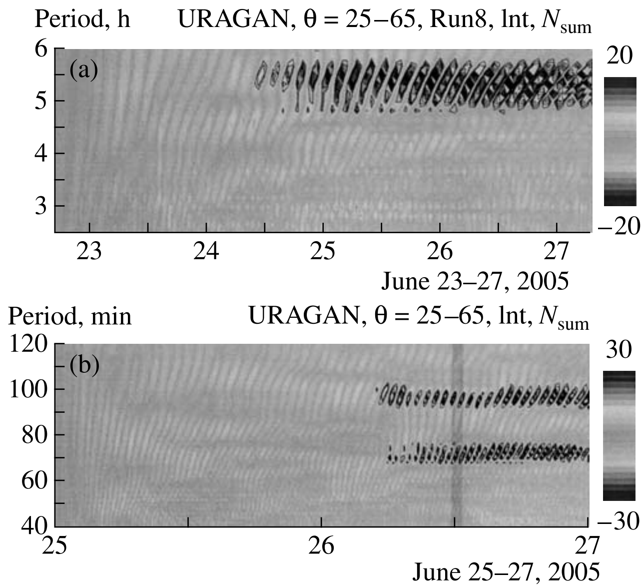

Fig. 2. Results of the wavelet analysis of the URAGAN data in the period of June 22–27, 2005 in the (a) long-period and (b) short-period ranges.

PRELIMINARY RESULTS

Currently, two muon hodoscopes are in operation at the Moscow Engineering Physics Institute: a TEMP scintillation detector [6] and a new URAGAN hodoscope [8, 9]. The latter uses streamer tubes as detectors and consists of individual removable assemblies (supermodules). Each supermodule has an area of 11.5 m^2 and an angular error of less than one degree. Figure 1 shows the data obtained with the URAGAN muon hodoscope on the muon flux anisotropy during the Forbush decrease of May 15, 2005: the azimuthal dependences of the relative deviation of the muon intensity from the mean in the range of zenith angles from 25° to 65° for four instants (indicated by arrows in panel a) and the azimuthal distribution obtained under quiet geomagnetic conditions (Fig. 1b, curve *5*). A local coordinate system is used: the *X* and *Y* axes are directed to the South–West and South–East, respectively. As the

Forbush decrease develops, a significant distortion of the azimuthal distribution of the muon flux is observed, whose peak shifts by approximately 60° during 3 h. This effect is due to the rotation of the Earth and the motion of the detector sensitivity cone with respect to the solar plasma cloud.

Figure 2 shows the results of the wavelet analysis of the data obtained in the period from June 23 to June 27, 2005 during the passage of a wide atmospheric front. Figure 2a exhibits a harmonic component with an oscillation period of about 5 h. The day of June 26, 2005, when intense atmospheric processes were detected in the North of the Moscow oblast (which resulted in a very intense hurricane near the towns of Dubna and Taldom), is of particular interest. In Fig. 2b, signals from the quasi-wave processes with periods of about 70 and 95 min are pronounced, which arose several hours before the arrival of the hurricane at Dubna (12 : 00 a.m.).

CONCLUSIONS

The use of cosmic rays (in particular, muons) as penetrating radiation and muon hodoscopes as peculiar instruments for obtaining "muon photographs" of the Earth's atmosphere and circumterrestrial space makes it possible to detect perturbed regions and trace the dynamics of their development and motion direction. The first results obtained with the new URAGAN muon hodoscope confirmed the possibility of using the same system to control the spatial distribution of the muon flux from the upper hemisphere in real time and detect various modulations, including wave ones, which are caused by perturbations in the Earth's atmosphere and circumterrestrial space.

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