Muon diagnostics of magnetosphere and atmosphere of the Earth

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***Abstract* — A new approach for remote monitoring of the heliosphere and the Earth's atmosphere and magnetosphere by means of cosmic ray muons is described. The physical principles of the method lie in a close connection of processes in the Earth's magnetosphere and atmosphere and variations of muon flux at the surface. This approach is based on simultaneous detection of cosmic ray muons coming 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. Such muon detectors (with total area more than 30 m^2) are being used for detection of spatial and temporal muon flux variations. The results of the obtained data analysis show that registration of muon flux in hodoscopic mode gives a new information about processes of its modulations and can be used for simultaneous study of magnetospheric processes, dynamics processes in the atmosphere and also of phenomena in the interplanetary space related with solar activity.**

I. Introduction

MUON diagnostics is the technique of remote monitoring based on simultaneous detection of muon flux from various directions of the upper sky hemisphere for the study of different dynamic processes in the atmosphere and magnetosphere of the Earth and in heliosphere. The intensity of cosmic rays 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 modulationsdetermined by geophysical cyclic processes and processes related with solar activity. Thus, muon flux variations bring information about both atmospheric and extra-atmospheric processes, and their separate investigation demands the development of new experimental approaches and new data analysis techniques. Basic conceptions of the theory and methods of determination of CR variations of atmospheric and extra-atmospheric origin were developed in the middle of XX century. The main goal of muon diagnostics is the solution of inverse task – the study of cosmic ray modulation processes using the analysis of spatial and temporal variations of muon flux at the Earth's surface.

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II. Physical principles of muon diagnostics

During the powerful solar CME, clouds of magnetized plasma can produce strong magnetic storms in magnetosphere of the Earth. Movement of solar plasma through the heliosphere disturbs magnetic field causing deflection of galactic CR (see Fig. 1). Variations of flux of muons generated in upper layers of the atmosphere and directed to the position of these clouds can be used for their localization and as a precursor of perturbation of the Earth's magnetosphere. If solar plasma cloud reaches the Earth vicinity, Forbush decreases of secondary CR which are detected by worldwide net on NM and muon detectors will appear.

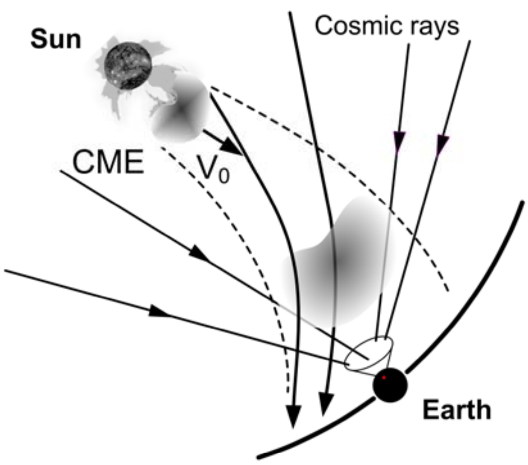

Fig. 1.Modulations of galactic cosmic rays related with solar activity

On the other hand, muon flux at the ground level is strongly related with different thermodynamic processes in the Earth' atmosphere at generation level (barometric, temperature effects) and with more complex wave processes in upper troposphere (inner gravitational waves of air density, significant density gradients, etc.), correlated with different turbulent and wave processes of geophysical origin (powerful thunderstorms, hurricanes, tornados, etc.), which are localized in space and time (see Fig.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 muon detector.

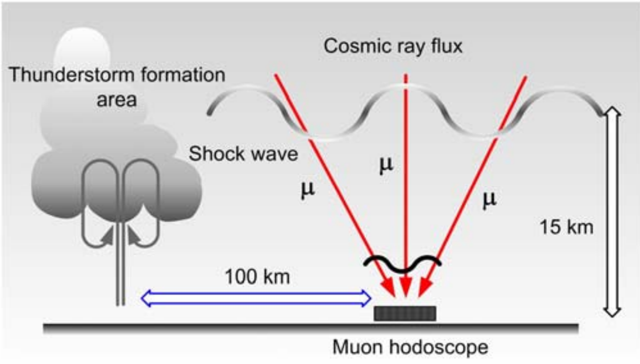

Fig2. Modulations of cosmic ray muon flux in upper layers of the atmosphere.

III. Detector requirements

For the first time the cosmic ray variations during strong magnetic perturbations (Forbush decreases) were detected in muon flux [1]. 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. Neutron monitors have one important advantage in comparison with muon detectors. They are not sensitive to atmosphere temperature, and dependence of detection rate on the pressure can be easily excluded [2, 3]. Existing muon telescopes can detect flux of atmospheric muons from one or several directions but do not have sufficient aperture to study spatial and temporal dynamics of muon flux.

To solve problems of muon diagnostics, the wide-aperture narrow angle muon detectors – 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 (better than 1 degree) and large sensitive area to provide necessary statistical accuracy of experimental data for all zenith and azimuth angular bins (in total about 10^6 events per hour). At total intensity of muon flux on the Earth's surface 0.01 cm^{-2} s^{-1} the area of detector must be not less than 10 m^2.

IV. Experimental setups

At present two muon hodoscopes are under operation in Moscow Engineering Physics Institute: scintillation detector TEMP [4] and new hodoscope URAGAN [5].

Muon hodoscope TEMP (see Fig.3) is the first wide-aperture narrow angle muon detector specially intended for the study of relations between CR muon flux variations and different modulation processes. TEMP setup consists of two pairs of layers with effective area 9 m^2. Each layer includes 128 narrow 3 m long scintillation strips with PMT. Angular resolution is better than 2 degree. During 1997 - 2002 exposition, the analysis of experimental data exhibited the existence of significant correlations between the active processes of atmospheric and extra-atmospheric origin and the wave characteristics of spatial and time muon flux variations and demonstrated the principal possibility of prediction of such phenomena.

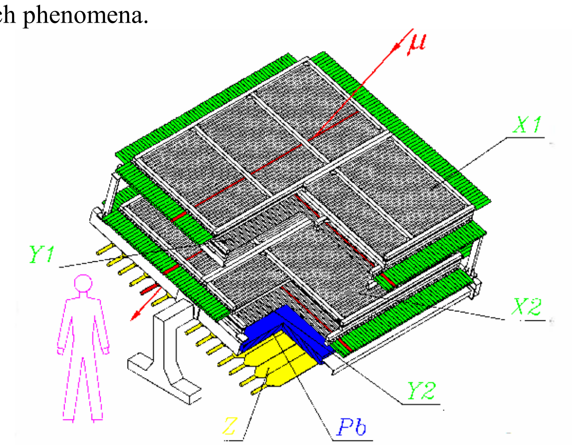

Fig. 3. Muon hodoscope TEMP

The new hodoscope URAGAN [1] was created on the basis of coordinate-tracking detector DECOR which is a part of Experimental complex NEVOD [2] and is deployed around the water Cherenkov calorimeter with volume 2000 m^3. DECOR has a modular structure and consist of two parts: the side detector – 8 vertical assemblies-supermodules (SM) in galleries around the Cherenkov calorimeter, and the top one – 4 horizontal SM located above the water tank. The basic elements are 3.5 m long streamer tube chambers with two coordinate external strip readout system. The total area is about 110 m^2.

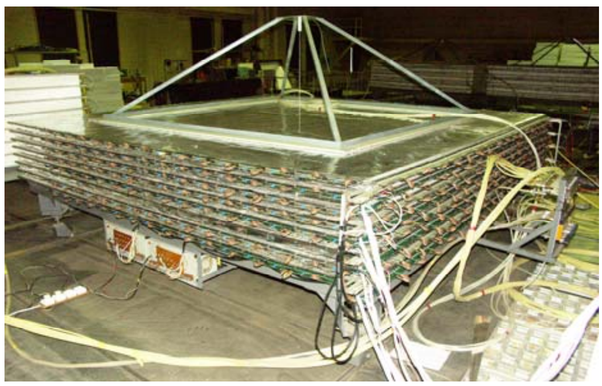

Fig. 4. A supermodule of muon hodoscope URAGAN

Each supermodule of top part of DECOR consists of eight layers of streamer tube chambers. Two top SM were re-assembled and equipped with new fast read-out electronic system developed specially to provide the detection of every muon from the upper hemisphere (< 80°) in the on-line mode. Each new supermodule (see Fig. 4) represents wide-aperture muon hodoscope with area about 11 m^2 and angular resolution ~ 0.7°. The track parameters (two projection angles) are on-line reconstructed by means of software program, based on the technique of histogramming of hits in each projection plane, and are accumulated as two-dimensional arrays (θ_x, θ_y) during one minute time interval. Such matrix represents the "muon image" of the upper hemisphere within the limits of detector acceptance with 1 minute exposition. The total counting rate is about 1700 Hz. The DAQ system of URAGAN provides the simultaneous detection of muon flux by means of several (up to four) supermodules thereby significantly increasing the signal-noise ratio.

V. Preliminary results

The first URAGAN SM was launched in 2005. During 2005 – 2006 experimental runs, the following investigations were carried out: anisotropy of muon flux during Forbush decreases; wave processes in the Earth's atmosphere; muon flux variations at power thunderstorms; study of modulation phenomena in the heliosphere on the basis of analysis of time sequences of «muon shots» of the upper sky hemisphere.

A. *Monitoring of modulation processes related with solar activity*

The dynamics of muon flux anisotropy obtained by means of URAGAN hodoscope during Forbush decrease on 15 May 2005 is presented in Figs. 5 - 6. The temporal dependence of total muon rate (in relative units) is shown in Fig. 5. The azimuth dependences of relative deviations of muon intensity from average value in zenith angular range 25 – 65 degrees are presented in the Fig. 6 for four moments of Forbush effect evolution pointed by arrows in Fig. 5.

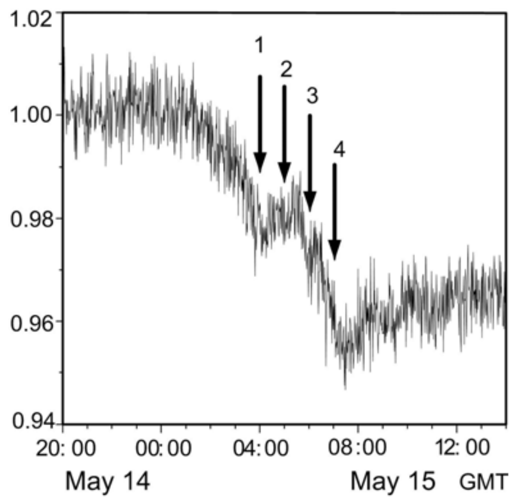

Fig. 5. Total muon rate of URAGAN supermodule during Forbush decrease 15 May 2005

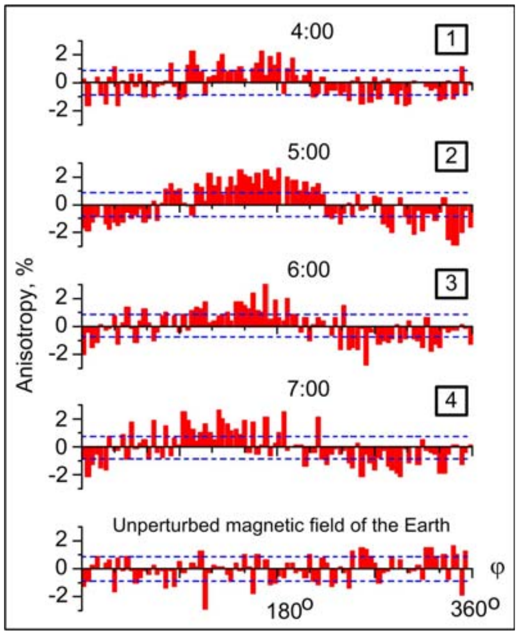

Fig.6. The dynamics of relative azimuth anisotropy of muon flux for different time moments on 15 May 2005: 1 – 4:00, 2 – 5:00, 3 – 6:00, 4 – 7:00 (UTC)

The azimuth angular distribution at undisturbed magnetic field conditions is shown in the bottom plot of Fig. 6. The appearance and development of the azimuth anisotropy of muon flux are clearly seen. The local coordinate system is used: X-axis is directed to South-West and Y-axis – to South-East. During the development of the Forbush decrease, a significant distortion of azimuth distribution of muon flux is observed. The maximum of distribution is shifting by the angle about 60°. This effect is determined by the Earth's rotation and movement of detector acceptance relative to solar plasma cloud. A more detailed discussion of obtained results is presented in [6].

B. *Monitoring of atmospheric processes*

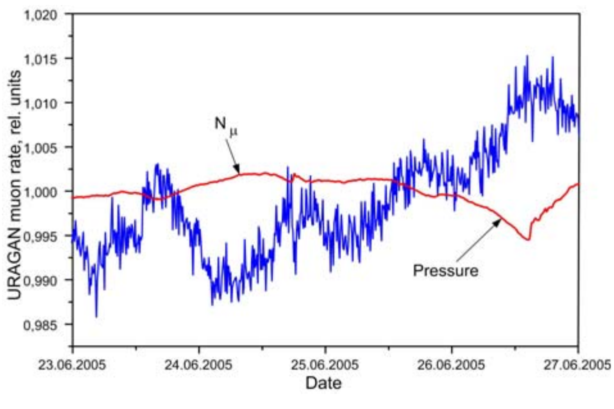

Fig. 7. URAGAN supermodule total rate and atmospheric pressure during 22 – 27 June 2005

In Fig. 7, the detected total muon rate and atmospheric pressure changes during period 23 – 27 June 2005 are shown.

The behavior of muon rate in the figure seems unusual since the expected close anti-correlation between atmospheric pressure and detected muon flux is not clearly observed. That time, above the European part of Russia a powerful atmospheric front was moving from North-West (see Fig.8) [7]. The arrival time of this front in Moscow is seen in Fig. 7 as the point of minimal pressure.

Results of wavelet analysis of URAGAN data accumulated during the period 23 – 27 June 2005 are presented in Figs.9-10 for two ranges of frequencies. The existence of harmonic component with a period about 5.5 hours appeared one day before the arrival of atmospheric front in Moscow is clearly seen in Fig.9.

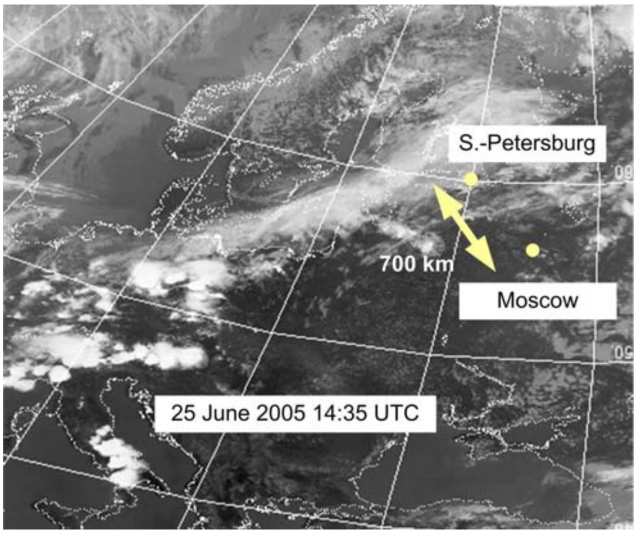

Fig.8. Atmospheric processes above European part of Russia (NOAA data)

During 26 June, in the North of Moscow region a strong hurricane generated by powerful turbulent processes at the atmospheric front appeared in Dubna town at 12:00 of local time. Dubna is located about 140 km far from Moscow. In Fig. 10, existence of two waves with periods about 95 and 70 minutes was found. These waves appeared some hours before the moment of hurricane arrival in Dubna, indicated in the picture by gray strip.

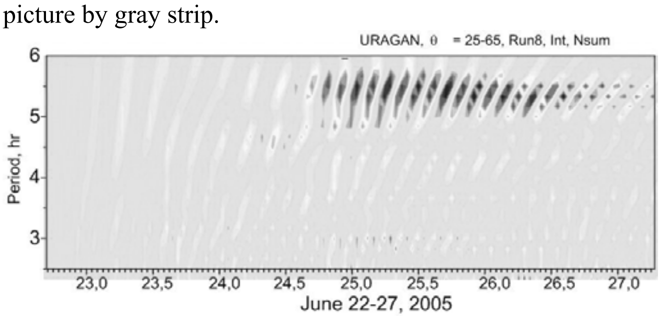

Fig.9. Wavelet transformation of URAGAN muon rate during June 22 – 27, 2005.

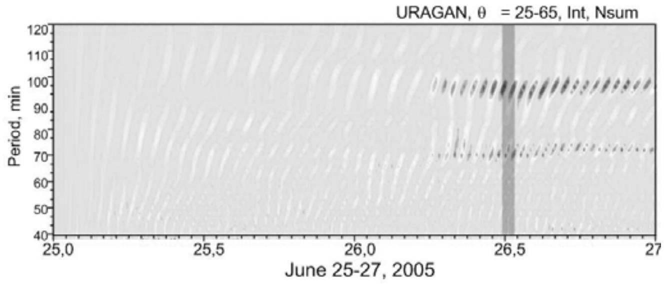

Fig.10. Analysis of URAGAN muon flux variations during hurricane in Dubna (June 26, 2005)

VI. Conclusion

The use of cosmic rays, in particular muons, as a penetrating component and muon hodoscopes as apparatus for detection of “muon images” of atmosphere and extra-terrestrial space allows to detect a disturbed areas and to observe the dynamics of their development and direction of their motion. First results obtained by means of new hodoscope URAGAN confirmed the possibility of the monitoring of spatial and temporal patterns of muon flux from the upper hemisphere in real time regime and to study different modulations, including quasi-periodic ones generated by perturbations of atmospheric and extra-atmospheric origin.

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