Study of correlations between thunderstorm phenomena and muon flux variations

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Abstract: Results of the study of correlations between thunderstorms happened in Moscow region in 2009 – 2010 and angular variations of muon flux detected by wide-aperture coordinate-tracking hodoscope URAGAN are presented. The approach to revealing of thunderstorm cells is based on the connection of thermodynamic processes in the atmosphere and modulations of cosmic ray muon flux at the Earth’s surface, since muon generation and propagation processes are sensitive to atmospheric conditions. Preliminary analysis shows that the proposed method allows to conduct effective monitoring of active turbulent processes over the area of thousands of sq. km and reveal thunderstorm cells from large distances. Moreover, wavelet analysis of muon flux variations allows advance detection of wave-like modulations initiated by powerful storms.

Keywords: Muon diagnostics, muon flux variations, cosmic rays, muon hodoscope, thunderstorms.

1 Introduction

At present, a new direction in investigations of various atmospheric processes, named muon diagnostics, based on penetrative ability of cosmic ray muons is being developed in MEPhI, Russia [1]. Muon flux is formed in the atmosphere at altitudes 15 – 20 km and is sensitive to the changes of main thermodynamic atmospheric parameters [2]. Therefore, any disturbances in the atmosphere modulate muon flux at the Earth’s surface, which gives the possibility to study these phenomena by means of sensitive muon detectors. In present paper, for the analysis of variations of muon flux at the surface caused by the processes in the atmosphere during the powerful thunderstorms over Moscow, the data of a new type of muon detector – hodoscope, capable of detecting muons simultaneously from different directions of the celestial hemisphere with a high angular and statistical accuracy are used.

2 Muon hodoscope URAGAN

Muon hodoscope URAGAN [3] (a wide-aperture coordinate-tracking detector) was constructed in the Scientific and Educational Centre NEVOD (MEPhI). Hodoscope is capable to detect muons simultaneously from all directions of the upper hemisphere and is used to study characteristics of muon flux variations as a function of spatial angle. URAGAN was launched in a permanent operation mode in 2005. At present, hodoscope consists of four identical supermodules (SM) with total area about 46 m², and total counting rate is about 5500 muons per second. Each SM is assembled of eight layers of gas-discharge chambers (streamer tubes) equipped with two-coordinate system of external readout strips and provides a high spatial and angular accuracy of muon track detection (correspondingly, 1 cm and 0.7°) in a wide range of zenith angles. The muon threshold energy depends on zenith angle and is in the range from 200 to 600 MeV. Every minute, angular distribution of muons is recorded in a two-dimensional angular matrix, which represents a snapshot of the upper hemisphere with 1-minute exposition. About three million matrices containing unique information on spatial-angular variations of the muon flux were collected during the experiment. The processing of the matrices sequence allows to obtain parameters of the muon flux anisotropy and the map of relative variations of muon flux from different directions [4].

3 Meteorological data

Various meteorological information was recorded and used to compare URAGAN data with the actual weather. Special passports with data necessary for the analysis of thunderstorm events were elaborated. Unfortunately,
weather information about thunderstorms in Moscow region is not complete. To obtain the most comprehensive picture of the thunderstorm activity, several sources of atmospheric data have been used, each of them served to indirectly verify the others. These sources are: 1) own barometric sensor of URAGAN; 2) information from the Moscow weather station (located about 20 kilometers from the hodoscope) [5]; 3) data of lightning detector which registers the intensity of lightnings over the Europe, including the European part of Russia [6]; 4) visual observations of thunderstorm processes in the vicinity of the experimental site. The main criterion of a thunderstorm event is a characteristic pressure peak, which in meteorology is called "pressure nose" (Fig. 1). Such burst of pressure usually appears during the passage of a thunderstorm cloud, but the amplitude of the burst may be different in the range from 0.5 to 5 mbar. Amplitude of the pressure peak depends on the features of the process; thunderclouds may appear at different altitudes and at different distances from the observer and can move with different speeds.

4 Methods of muon hodoscope data processing

The data accumulated by the DAQ of the URAGAN setup in on-line regime during 1-minute exposition are saved in three types of two-dimensional matrix format with dimensions 91×91 cells: both zenith and azimuth angles (θ, φ); projections of zenith angle (θX, φ) of the muon track (in local coordinate system); the matrix with regular bins in (tan θX, tan φ) which is used for a visual illustration of muon flux variations. In order to smooth Poisson cell-to-cell fluctuations, a two-dimensional Gaussian filter is applied. Then for every cell of the matrix the mean number of muons (averaged during preceding 24 hours and corrected for atmospheric pressure) is subtracted; the difference is divided by the statistical uncertainty σRMS of the smoothed matrix, estimated for every cell. In Fig. 2, the matrix of muon intensity variations calculated for 5-minute interval for the thunderstorm event of July 14, 2009 is presented. Scale in the figure denote values of muon intensity changes in σRMS units; tints represent excess or deficit of muons arriving from a certain direction. To combine the matrix and the map, straight lines are drawn from the point of detector location in directions corresponding to the cells of the angular matrices, and points of intersection of these lines with the level of muon generation (16 km altitude) are defined. After that, the intersection points are projected to the surface of the Earth. Thus, the position of the angular cell on the map is the projection of muon generation area. Not the whole matrix is presented in the picture, but the circle with its central part limited by 75° zenith angle for a convenient visual perception. Thin orthogonal lines identify North-South and West-East directions. The inner thin concentric circles correspond to zenith angles 30°, 45° and 60°. Statistics of the image exceeds one million tracks. For a quiet atmosphere, perturbation in muon flux is practically not visible; however, in the matrix presented in the figure a spatial heterogeneity of muon flux changes during the thunderstorm disturbance is seen very well. In some areas, lowering of muon flux exceeded 4 σRMS.

As a quantitative characteristic of muon flux angular variations, the local anisotropy vector is used, which indicates the average arrival direction of muons. Local anisotropy vector A is defined as the sum of unit vectors, each representing the direction of the individual track, normalized to the total number of muons [7]. The length of the vector depends on the shape of the angular distribution of muons. The average direction of anisotropy vector is very close to the vertical, but during atmospheric disturbances rather strong deviations from the mean value are observed. For the analysis, the absolute value of the anisotropy vector and two projections of this vector onto horizontal plane - the south (Aδ) and the east (Aφ) ones – are used. In addition, the value of the vector of the relative anisotropy P (the difference between the local vector of anisotropy in the current interval of time and that averaged for a long time period) and its projection on the horizontal plane φ are considered.

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the average (for all cells of the matrix) deviation of the integral muon rate. The surveying of the sky in the “muon light” allows separate areas of the muon flux changes which can be considered as a response of the hodoscope to perturbations related with irregularities of the air density in the region of the thunderstorm cloud.

5 Study of muon flux variations during thunderstorms

During the periods May-September 2009 and 2010, 39 thunderstorm events were revealed in Moscow region, and for 15 most powerful of them (the power was estimated by the height of the pressure nose, more than 0.5 mbar) URAGAN data were analyzed. In most events during thunderstorms, the reaction in integral counting rate of URAGAN is observed. Fig. 3 shows the correlation of the decrease in total counting rate with the maximum pressure increase for thunderstorm events in which the deviation of the counting rate exceeded $1 \sigma_{RMS}$.

![Figure 3. Correlation of counting rate decrease with the amplitude of the pressure nose.](image)

The root-mean-square (RMS) deviations were estimated over periods equal to one day (12 h before and 12 h after the pressure noses). The value of the total counting rate decrease in $\sigma_{RMS}$ units is defined as the difference between the value at the minimum and the average per day divided by sigma. The tendency for increasing response in the total counting rate with the value of the pressure peak is observed in Fig. 3, although the correlation is not clearly seen. Noteworthy, the counting rate is corrected for atmospheric pressure at the observation point, so this dependence cannot be explained by the usual barometric effect. Examples of plots of various parameters which are calculated basing on the matrix data, are presented in Fig. 4: left – the absolute value of the vector of the local anisotropy and two its projections, right – module of the vector of relative anisotropy and its horizontal projection. The graphs correspond to the thunderstorm of May 12, 2009.

The response is observed in all these parameters; the vector of the local anisotropy and its projections have a minimum, and the vector of the relative anisotropy - on the contrary, a maximum. Almost all parameters exhibit maximum deviation at the same time - 11:25 (except $A_3$, at 11:20). Maximum of the pressure in this event was also marked at 11:25.

The analysis of powerful storms of 2009 – 2010 reveals a definite delay in the time of reaction in the counting rate compared to the pressure nose. On average, the delay is about 25 minutes. The exception is the thunderstorm of August 1, 2010 when URAGAN counting rate reacted much earlier – almost two hours before the pressure nose peak. The time differences for analyzed events are presented in Fig. 5.

Development of thunderstorm cells is accompanied by powerful turbulent and convective processes which cause different wave processes in the upper troposphere. In Fig. 6, results of wavelet analysis of wave processes in the sequence of URAGAN counting rates during the period of thunderstorm of May 12, 2009 evolution are presented. The moment of thunderstorm passing above the point of observation is clearly seen. Also waves with periods of around 40 and 65 minutes that appeared several hours before the event beginning are well seen in the data, too. The distribution of wave periods identified in the URAGAN data in thunderstorm events of 2009 – 2010 in the range 20 – 120 minutes before the storm starts is presented in Fig. 7. One can see that most characteristic periods correspond to 40-50 min, 60-70 min and 90-100 min. The distribution of found periods for the range 1 – 6 h is shown in Fig. 8. The histogram has a maximum at 3 – 4 hours.
6 Conclusion

The performed analysis of muon hodoscope data obtained during the summers 2009 and 2010 has shown that the flux of cosmic ray muons is sensitive to local atmospheric disturbances. The reaction of the URAGAN integral counting rate to the passage of thunderstorm cells has been found in 20 events from 25. But the response in angular characteristics of the flux is observed in practically all events. This result indicates promising perspectives of application of cosmic rays as a tool for monitoring of atmospheric phenomena.

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8 References