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Effects Observed in the Muon Flux during Thunderstorms, According to Data from the URAGAN Muon Hodoscope

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Abstract—Results from an analysis of URAGAN muon hodoscope data are used to identify effects observed in connection with thunderstorms recorded above and at considerable distances from the setup. These include quasiperiodic disturbances of the muon flux characteristics, reductions in the count rate, and changes in the muon flux anisotropy. An algorithm is created for selecting thunderstorm events that have a response in the muon data. It is found that abrupt drops in the muon count rate are not directly related to precipitation.

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INTRODUCTION

The URAGAN muon hodoscope (MH) [1] is a wide-aperture coordinate detector that continuously records muons of cosmic rays at an altitude of 173 m above sea level. The URAGAN MH allows the simultaneous recording of muons in a wide range of zenith angles (from 0° to 80°) with high angular accuracy (0.8°).

The muon flux forms in the upper layers of the atmosphere and is sensitive to changes in its parameters. The URAGAN MH data obtained in spring–summer (April–September) periods are analyzed to study the effects observed in the muon flux during thunderstorms.

The time series of the muon count rate ($I_{\rm sum}$) and the projections of the relative anisotropy vector of the muon flux ($\vec{r}$) on the geographical axes and the $\vec{z}$ axis ($r_{\rm south}$, $r_{\rm east}$, and r_z) are considered, along with results from wavelet analyses of $I_{\rm sum}$ and characteristics of zenith-angular distributions. Definitions of these parameters are given in [2]. Muonographs are used that are visualized matrices of changes in the angular distribution of the recorded flux over the last 24 h, expressed in units of statistical error. An example of a muonograph is presented in Fig. 1 (on the right). The dark spot in the center indicates a muon-deficient region. Eighty-one thunderstorm events were analyzed for the 2014–2019 period. The procedure for this analysis was described in [2, 3].

Wavelet analysis of the time series of $I_{\rm sum}$, the magnitude of the local anisotropy vector (A), and the horizontal projection of $\vec{r}$ ($I_{\rm hor}$) showed the muon flux experiences quasiperiodic perturbations during periods of thunderstorm activity. The procedure for wavelet analysis was described in [4], and preliminary results were given in [3]. Wave processes can be detected in the characteristics of the muon flux long before the moment a thunderstorm passes by the URAGAN MH, and can also arise as a result of thunderstorm activity occurring at considerable distances from Moscow.

Examination of the time series of the muon flux characteristics shows that sharp changes in the values of $I_{\rm sum}$, $r_{\rm south}$, $r_{\rm east}$, and r_z lasting around 15 min are observed during periods of thunderstorms. Table 1 compares the average values of these characteristics for thunderstorm events, determined using data from weather stations and the meteorological DMRL-S Doppler radar at the Central Aerological Observatory [5] for the duration of the spring–summer periods of 2014–2018. The data in Table 1 show that during thunderstorm events, $I_{\rm sum}$ drops relative to the average value throughout the period, indicating a lack of muons. The absolute values of projections $r_{\rm east}$ (the east–west axis) and $r_{\rm south}$ (the north–south axis) also fall, while that of projection r_z rises. The average direction of muon arrival during thunderstorms shifts southwest, relative to that of the entire period.

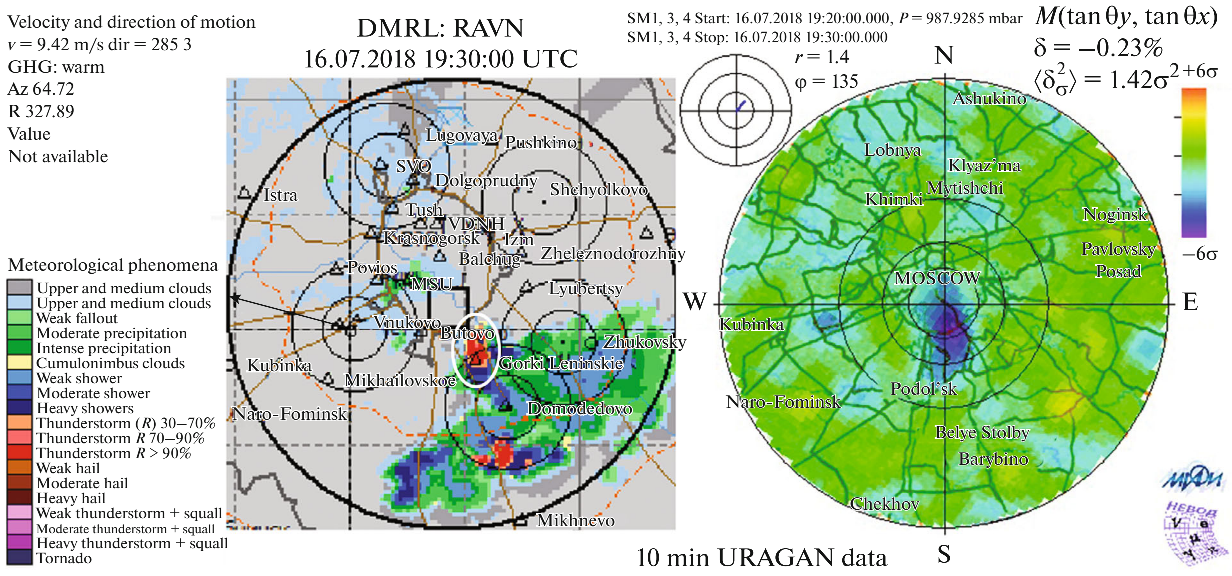

Fig. 1. Muonograph for the event on July 16, 2018. Right: Images of the 10-min averaged matrix of changes in the angular distribution of the muon flux. Left: Map of meteorological phenomena according to DMRL data. The white oval on the meteorological map marks the area of thunderstorm activity that in the muonograph corresponds to the dark region of few muons.

The drops in I_{sum} and changes in the anisotropy of the muon flux are easily followed in the muonographs of thunderstorm events. An examination of them shows the URAGAN MH responded to them even when a thunderstorm was not observed directly above the setup. Figure 1 shows this response for the event on July 16, 2018. On the left of the figure, there is a meteorological map obtained using data from the DMRL-S at the Central Aerological Observatory; on the right is the corresponding muonograph. Note the agreement between the area of thunderstorm activity (highlighted on the meteorological map) and the region with the lack of muons (dark area) on the muonograph. Neither thunderstorm activity nor precipitation was in this case observed above the URAGAN MH.

An algorithm was developed on the basis of these effects to identify thunderstorm events that had a response in the muon data. This was done by separating significant deviations (spikes) of the current values of I_{sum}, r_{south}, r_{east} and r_z from their sliding average. The first stage of development was described in [6]. Dates had to be be separated when there was a response from the URAGAN MH to a meteorological phenomenon recorded by weather stations. The dates of thunderstorms and showers were recorded, while the reaction to showers was weak (only 11% of all dates were determined). When information from the DMRL-S meteorological maps was included, it was found that the low efficiency of recording showers was due to mainly thunderstorm events being selected.

The algorithm was modified (a time interval of 1 h was assumed to be an event) and used to process data for April–September 2014–2019. A total of 199 operations were recorded, 8 of which were malfunctions (4% of the total). According to the website's data [7], no thunderstorms were observed 12 h before or after 14 operations in Moscow oblast (7% of the total). It was found that most (more than 90%) of the spikes in the muon flux characteristics not related to extra-atmospheric effects were associated with thunderstorm activity.

There are several possible reasons for the brief (5 to 15 min) drops in I_{sum} by values of about 1% during

Table 1. Comparison of the average values of different muon flux characteristics for thunderstorm events and the duration of the spring–summer periods of 2014–2018

Characteristic	I_{sum}, s^{-1}	r_{east}, 10^{-4}	r_{south}, 10^{-4}	r_z, 10^{-4}
Thunderstorms	1387.8 ± 0.7	1.1 ± 0.2	−2.0 ± 0.1	11.0 ± 0.1
Spring–summer periods	1401.72 ± 0.13	1.75 ± 0.2	−2.7 ± 0.2	8.5 ± 0.2

periods of thunderstorm activity. The first is the barometric effect. It is considered when calculating I_{sum} and cannot be the main explanation. The second is the influence of the electric field of a thundercloud [8–10]. However, it does not explain why there were none of the expected increases in I_{sum} caused by the alternating nature of atmospheric electric fields, or the presence of both μ^+ and μ^- in the composition of cosmic rays [11]. The third possible reason is the influence of water. Precipitation can increase the absorption of muons and lead to drops in I_{sum}. The coincidence of precipitation and drops in I_{sum} over time, cases where similar amounts of precipitation did not produce a strong drop in I_{sum}, and events where a drop was observed with no recorded precipitation, were all noted.

Data from January 1, 2014, to December 31, 2018, were examined to compare I_{sum} and levels of precipitation. Five-minute time series obtained by the URAGAN MH and the Vaisala weather station were used. Correlations were constructed for the entire period and those of the summer (April–September) and winter (October–March). Correlations were constructed for thunderstorm and non-thunderstorm periods. They were also divided according to season. Thunderstorm activity was determined using data from weather stations, DMRL-S maps, and information from the website [7]. All data from 12 h before and after a thunderstorm recorded at one of the weather stations or by the DMRL-S radar were included in the corresponding periods.

Coefficients of correlation were obtained for the dependences of I_{sum}, I_{sum} spikes, and I_{sum} spikes of more than 3σ on humidity and precipitation over 5 min, 1 h, and 24 h. The coefficients of correlation did not exceed 0.4 in absolute value for any of the considered dependences with a sufficient number of points and p criteria of <0.05 (i.e., no linear regression was observed).

The percentage of significant I_{sum} spikes 1 h before or after precipitation was observed at the Vaisala weather station was 16% throughout the period, 21% in summer, and 9% in winter. This testifies to thunderstorm activity being a source of the relationship between significant I_{sum} spikes and precipitation. When thunderstorm events were excluded from consideration, the percentage was 9% for the entire period, 10% in summer, and 9% in winter. When only thunderstorm periods were considered, the percentage was 41% for the entire period, 41% in summer, and 50% in winter.

We may conclude that sharp drops in I_{sum} are not directly related to precipitation but are associated with it during periods of thunderstorm activity. No dependence of I_{sum} on the amount of precipitation was observed throughout the period.

CONCLUSIONS

It was shown that the URAGAN MH responds to a thunderstorm event (quasi-periodic perturbations of flow characteristics, drops in the count rate, and changes in anisotropy) both when the thunderstorm passes over the detector and when one occurs at a considerable distance from the setup. An algorithm was developed for identifying thunderstorm events with a response in muon data. It was used to show that most of the spikes not related to extra-atmospheric effects in the characteristics of the muon flux were associated with thunderstorm activity. According to the URAGAN MH data, drops in the muon count rate are not directly caused by precipitation, but they are associated with it during periods of thunderstorm activity.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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