Variations in the intensity of cosmic ray muon bundles according to DECOR data 2012-2017

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Abstract. Investigation of variations in the intensity of cosmic ray muon bundles detected at the ground level with the coordinate-tracking detector DECOR over a long period of observations is considered. It has been found that the measured intensity of the events exhibits clear seasonal variations, repeated every year of observations. These variations are caused by changes in atmospheric conditions. Correlations of the intensity of muon bundles with atmospheric pressure, mean air temperature and the altitude of the fixed residual atmospheric pressure levels have been analyzed.

1. Introduction
The rate of the events resulting from interactions of cosmic rays in the atmosphere and detected on the Earth's surface is subjected to changes caused by atmospheric conditions (atmospheric pressure, temperature, etc.). The most well studied are variations in the intensity of single cosmic ray muons [1].

However, it is important to note that the values of meteorological effects, as well as the physical processes responsible for their formation, are different for different cosmic ray components (muon, hadron, electron-photon ones) and events of different classes.

The correct understanding of the influence of atmospheric effects on the intensity of registered events is important for accurate comparison of the data of experiments conducted in different conditions and introduction of necessary corrections.

In the present paper, seasonal variations and meteorological effects in the intensity of muon bundles detected at the ground level are considered. Some preliminary results based on the initial part of the experimental material were published earlier [2].

2. Experimental setup and data
Coordinate-tracking detector DECOR [3] (MEPhI, Moscow, 165 m a.s.l.) consists of eight supermodules (SMs) deployed around the Cherenkov water detector (CWD) NEVOD. Each supermodule includes eight vertical planes of streamer tubes. Total area of DECOR is about 70 m². Angular accuracy of muon track reconstruction in the SM is better than 1 degree, spatial accuracy is better than 1 cm.

The muon bundle is the event with a simultaneous passage of several genetically related muons through the setup. The main sources of muon bundles are decays of pions and kaons generated in nuclear cascades initiated in the atmosphere by high energy primary cosmic ray particles. The selection of muon bundles in DECOR is based on the assumption that the tracks of muons generated in
the atmosphere at large distances from the setup are nearly parallel to each other. Muon bundle events must contain at least 3 quasiparallel particles detected in 3 different DECOR SMs. The events with muon bundles in the interval of zenith angles from 15 to 70 degrees were analysed. In figure 1, an example of muon bundle event in DECOR is presented.

![Muon tracks in DECOR SMs](image)

**Figure 1.** An example of muon bundle registered in the DECOR detector.

Long-term measurements of the muon bundles are carried out at the NEVOD experimental complex from spring 2012. The results of the analysis of the data on the intensity of muon bundles detected by the DECOR detector during five years of observations (from May 2012 to June 2017) are presented. About 7.4 million events with muon bundles have been accumulated. The total live observation time is 30.8 thousand hours.

3. **Seasonal variations in the intensity of muon bundles**

It has been found that the measured intensity of the events shows clear seasonal variations, repeated every year of observations (see figure 2).

![Seasonal variations in the rate of muon bundle detection](image)

**Figure 2.** Seasonal variations in the rate of muon bundle detection during the observation period from 03.05.2012 to 28.06.2017.
Every point in the figure corresponds to one experimental run with a duration from 10 to 40 h, the curve represents the results of the fitting with a harmonic function which has the form:

\[ F(t_i) = C + A \cos \left(2 \pi \left(\frac{t_i - t_m}{t_0}\right)\right), \tag{1} \]

where \( t_i \) is the time (in days from the beginning of 2012) corresponding to the middle of the \( i \)-th data set, \( t_0 \) is the period equal to the average calendar year (365.24 days), \( t_m \) is the time moment in the year corresponding to the maximum of the first annual harmonic. Parameters \[ C = 239.17 \pm 0.09 \text{ h}^{-1}, \quad A = 13.30 \pm 0.12 \text{ h}^{-1}, \quad \text{and} \quad t_m = 24.80 \pm 0.55 \text{ days} \] were obtained by the weighted least squares technique. The intensity of muon bundles in winter is considerably higher than in summer (on average, the difference reaches 11%). The maximum intensity is observed in January, and the minimum in July.

4. Atmospheric effects in muon bundle intensity

On the background of the seasonal changes, short-term variations with duration of few days are seen in figure 2. It is naturally to assume that these changes are related to atmospheric conditions. This section describes atmospheric effects (barometric and temperature ones) in the intensity of muon bundles registered on the ground level, as well as correlations of the rate of muon bundles with the altitudes of the fixed pressure levels.

4.1. Barometric and temperature effects

The atmospheric pressure was determined from the sensor located in the NEVOD building. As a source of information about the temperature of the atmosphere, the retrospective data of the GDAS model (Global Data Assimilation System) [4] were used.

The mass average temperature of the atmospheric air has been defined as

\[ T_{ma} = \frac{\int_{p_1}^{p_2} T(P) dP}{\int_{p_1}^{p_2} dP}, \tag{2} \]

where \( T(P) \) is the air temperature at the pressure level \( P \), and as integration limits \( P_1 \) and \( P_2 \) the values 10 and 950 mbar have been chosen. After that, for every set of data with muon bundles, the value of the mass average temperature was estimated as a simple average of 3-hour GDAS data within the start/stop limits of the run.

Figures 3 and 4 represent correlations of muon bundle counting rate with atmospheric pressure and mass average temperature of atmospheric air. In order to estimate the influence of barometric and temperature effects, we fitted the data with a following phenomenological formula:

\[ F = F_0 (1 + \beta_p \Delta P)(1 + \beta_T \Delta T), \quad \Delta P = <P> - <P>, \quad \Delta T = <T> - <T>. \tag{3} \]

Here \(<P>\) and \(<T>\) are the average values of atmospheric pressure and temperature for the observation period. Barometric and temperature coefficients \( \beta_p = -0.376 \pm 0.005 \% / \text{mm Hg} \) and \( \beta_T = -0.807 \pm 0.006 \% / \text{K} \) were found iteratively.

In both cases, strong correlations of the measured muon bundle rate with the considered parameters of the atmosphere are observed. However, comparison of the correlation coefficients of the muon bundle intensity with atmospheric pressure \( R_p = -0.91 \) and the mean temperature of the atmospheric air \( R_t = -0.97 \) shows that the main factor that influences the muon bundle intensity is the temperature effect, which explains strong seasonal variations (figure 2).
4.2. Correlations with the altitude of the fixed pressure levels

One of the parameters characterizing the altitude profile of the atmosphere is the altitude of the isobaric surface (level of a fixed residual atmospheric pressure). We have analyzed correlations of the muon bundle rate with the altitudes of isobaric surfaces. Dependence of the obtained values of the correlation coefficient of the bundle rate with the altitudes of the different fixed pressure levels is shown in figure 5. The closest correlations ($R_H = -0.970$, almost functional dependence) are revealed for a residual pressure of 500 mbar ($<H> = 5.52 \text{ km}$); for levels less than 300 and more than 700 mbar, the correlations are rapidly destroying. This indicates that most of the muons detected in the bundles are formed in the troposphere at altitudes of 3 to 9 km above sea level. A slightly higher value of the correlation coefficient ($R_H = -0.971$) is obtained if we use not linear but a power-law dependence of the event rate on the altitude of the isobaric surface in the form:

$$F = F_0 (H/\langle H \rangle)^\alpha. \quad (4)$$

The results of fitting the experimental data with a power function of the altitude (a straight line in a double logarithmic scale) for a 500 mbar level are shown in the figure 6 (the resulting slope is $\alpha = -1.689 \pm 0.011$).

Figure 6. Correlations of the event rate with the altitude of the isobaric surface on the residual pressure level.

Figure 4. Correlations of muon bundle rate with the atmospheric pressure.
5. Geometrical mechanism of the bundle intensity variations

The characteristic energies of muons in the bundles are tens of GeV, and therefore the observed meteorological effects cannot be explained by the absorption and/or decay of low-energy particles in the atmosphere, typical for single muons detected at the ground level [5]. Alternative explanation of variations in the muon bundle intensity was suggested in our paper earlier [2].

Muons are created near the extensive air shower (EAS) core, and their spread at the ground level is determined mainly by transverse momenta at production and decay of parent mesons, and is also proportional to the generation altitude. Changes in the state of the atmosphere lead to variations of the geometrical altitude of muon bundle formation, and hence to scaling variations of the muon lateral distribution function (LDF) at the observation level (see figure 7). As was shown in [6], the spectrum of events with the local muon density $D$ and, consequently, the intensity of muon bundles registered in a small area detector is proportional to an integral of the LDF:

$$F(\geq D) = N_0 D^{-\beta} \int [\rho(E_0, r)]^{\beta} dS,$$

where $\rho(E_0, r)$ is the lateral distribution function of muons in a plane orthogonal to the shower axis, $E_0$ is some effective primary energy, $r$ is the point in the EAS cross section (corresponding to the detector location), and $\beta$ is an integral local muon density spectrum slope. In these circumstances, the event intensity should follow a power law $F \sim (H/\langle H \rangle)^{\alpha}$, where $\alpha = -2(\beta - 1)$. The experimental power law index $\alpha = -1.69$ (or $\beta = 1.84$) is in a reasonable agreement with the expected one if we take into account the independently estimated local muon density spectrum slope $\beta = 1.96 \pm 0.02$ [6].

![Figure 7](image)

Figure 7. Illustration of the increase of the radial spread of muons (left) and of changes of the LDF of EAS muons (right) at the heating of the atmosphere.

6. An “inverse” task of atmospheric parameters estimation

Close correlations between muon bundle intensity and $H_{500}$ (the altitude of 500 mbar residual pressure level) allow us to consider an “inverse” task – estimation of the isobaric surface altitude from the measured event rate.

The points in figure 8 represent the altitudes of 500 mbar residual pressure level reconstructed from DECOR muon bundle data for the period autumn 2016 – winter 2017. These estimates of the altitudes have been obtained from the measured event rates using equation (4) with the parameters determined in the subsection 4.2. The line in the figure corresponds to the data of independent meteorological observations (GDAS database [4]). The agreement, even in minor details, is impressive.
Figure 8. Dependence of the altitude of 500 mbar residual atmospheric pressure level on time.

7. Conclusion
Data of a five-year experiment on detection of muon bundles at the ground level conducted with the coordinate-tracking detector DECOR have been analyzed. It has been found that significant variations of atmospheric origin is the main factor that influences the rate of muon bundles. It is shown that the variations in the intensity of the bundles are well described in the framework of a simple geometrical model of variation mechanism.

Acknowledgments
The work was performed at the Unique Scientific Facility Experimental complex NEVOD with a state support provided by the RF Ministry of Education and Science (MEPhI Academic Excellence Project 02.a03.21.0005 and government task).

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