Atmospheric effects in the intensity of muon bundles and geometrical mechanism of their formation

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Abstract. Temporal changes in the intensity of muon bundles produced as a result of interactions of primary cosmic ray particles with energies of the order of 10^{15} eV and detected at the ground level are analyzed. Seasonal variations, barometric and temperature effects, and correlations with the altitudes of various levels of residual pressure are considered. It is shown that muon bundle intensity variations are well explained in frame of a simple mechanism related with changes of the muon lateral distribution function at the observation level caused by geometrical changes of the effective altitude of the formation of the bundles.

1. Introduction

The rate of the events generated as a result of interactions of cosmic rays in the atmosphere and detected on the Earth's surface is subject to variations caused by the atmospheric conditions [1]. The correct understanding of the influence of atmospheric effects is important for comparison of data of the experiments conducted in different geographical points and conditions, and for introduction of necessary corrections. It is important to note however that the values of the meteorological effects as well as the physical processes responsible for their formation are different for different cosmic ray components (muon, hadronic, electron-photon) and for events of different classes.

In present paper, variations in the intensity of muon bundles detected at the ground level with the coordinate-tracking detector DECOR [2] are considered. The 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. Already in the first experiments on muon bundle detection with DECOR conducted in 2004 – 2007, significant changes of the rate of registered events were noticed [3]. For the first time, experimental estimates of the barometric and temperature coefficients for muon bundle intensity were obtained, which appeared unexpectedly high. As a possible interpretation of the results, a new mechanism related with a geometrical transformation of the lateral distribution function of EAS muons for a varying temperature profile of the atmosphere was suggested.

Unfortunately, preceding series of measurements with DECOR were relatively short and did not exceed 6 – 7 month; in particular, no data were taken in summer periods (from July to September). Starting from 2012, nearly continuous measurements are conducted which create necessary pre-requisites for the analysis of variations on a qualitatively new level. Below, the results of the analysis of the data on the intensity of muon bundles detected during three years of observations are presented.

2. Experimental data and seasonal variations

The coordinate-tracking detector DECOR [2] is a part of the NEVOD experimental complex. It is deployed in the galleries of the NEVOD building in MEPhI (Moscow, 55.7º N, 37.7º E, ~ 165 m a.s.l.) and consists of 8 assemblies (supermodules, SMs), each with area of 8.4 m^2. The supermodule includes 8 vertical planes of plastic streamer tube chambers equipped with two-coordinate external strip readout system. Spatial and angular accuracies of muon track reconstruction in the SM are better than 1 cm and 1º, respectively.

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. At a trigger level, the events with at least three (of eight) hit SMs are recorded. At the off-line data processing, the geometry reconstruction of the tracks in the SMs is performed, and candidate events with at least 3 quasi-parallel tracks (coinciding in direction within a 5º-cone) detected in 3 different SMs of DECOR are selected. Distribution of the events in zenith angle is rather wide; about 90% of the detected bundles lie in the range from 21º to 65º with a median value near 42º. According to earlier estimates [4], these bundles are mainly formed as a result of interactions of primary cosmic ray particles with typical energies of $10^{15} – 10^{16}$ eV.

Experimental data are accumulated as a sequence of separate sets (runs) with duration of up to ~ 40 h. Short runs (less than 10 h, comprising about 3% of the total statistics) have been excluded from the present analysis. As a result, we left with 590 runs corresponding to the total live time of 17,760 h, containing about 4.4 million muon bundles registered over the period from May 03, 2012 to April 08, 2015. For every run, the number of the selected muon bundles, live registration time, start/stop moments, average atmospheric pressure at the setup location and other parameters have been determined. The mean rate of muon bundle events during observations equals to 248.1 per hour. The measured time dependence of the rate of muon bundle detection over the period of observations is shown in figure 1. Every point represents one run data; the error bars indicate statistical uncertainties.

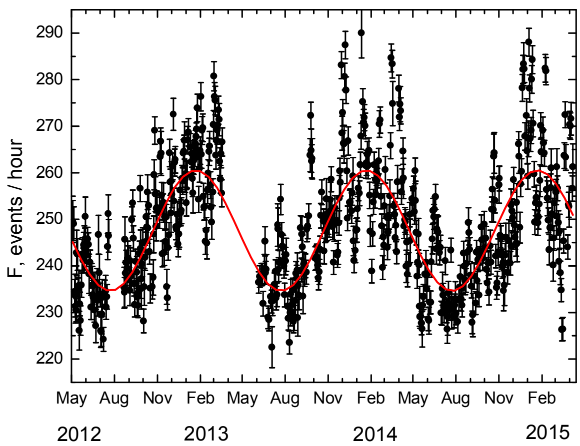

Figure 1. Temporal variations of the muon bundle detection rate. The smooth curve represents the first annual harmonic.

As follows from the figure, clear seasonal variations repeated every year are observed in the event rate. The smooth curve in the figure represents the first annual harmonic obtained by means of a weighted least square fitting of the data. On the average, the intensity of muon bundles detected in winter and in summer differs by more than 10%; the maximum intensity is typically observed in the second half of January, and the minimal one in July.

3. Barometric and temperature effects

On the background of smooth seasonal variations in the event intensity, short-term deviations from an overall harmonic dependence with duration of the order of few days are observed. It is natural to assume that these deviations are related with the changes of the atmospheric conditions. In order to estimate the influence of barometric and temperature effects, we fitted the data with a following phenomenological formula:

$$F = F_0(1+\beta_P\Delta P)(1+\beta_T\Delta T);\ \Delta P = P-<P>;\ \Delta T = T-<T>. \quad (1)$$

Here <*P*> and <*T*> are average values of atmospheric pressure and temperature for the observation period. As a temperature characteristic of the atmosphere, we use here the mass average temperature of the air calculated from the retrospective data of the GDAS (Global Data Assimilation System) model [5]. Mean values of the ground pressure and the mass average temperature were equal to 746.7 mm Hg and 247.0 K, respectively. Barometric and temperature coefficients β_P and β_T were found iteratively. Iteration procedure rapidly converges, and the estimates of the parameters for the second and third iterations differ by less than their statistical errors. Correlations of muon bundle detection rate with atmospheric pressure and mass average temperature air are shown in figures 2 and 3.

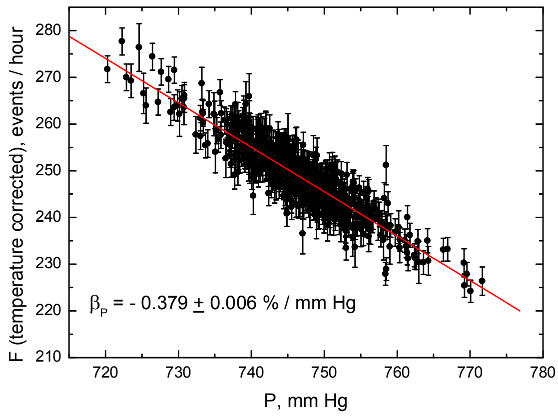

Figure 2. Correlations of the event rate (corrected for the temperature effect) with barometric pressure at the observation point.

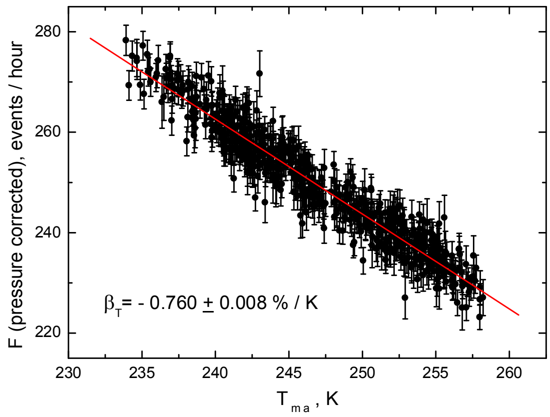

Figure 3. Correlations of the event rate (corrected for the barometric effect) with the mass average air temperature T_{ma}.

4. Correlations with the altitude of the fixed pressure levels

Among other parameters, information on the altitude of the isobar surface for a set of residual pressure levels P_L is available in the GDAS data [3]. We have analysed correlations of the muon bundle detection rate with the altitude of various pressure levels and fitted the observed dependence as:

$$F = F_0(1+\beta_H\Delta H);\ \Delta H = H-<H>. \quad (2)$$

Here <*H*> is the average altitude of a certain pressure level, and β_H is the corresponding coefficient of a linear regression. The results for several values of the residual pressure are summarized in table 1. As seen from the table, the most close correlations (R_H = - 0.971, which evidences for an almost functional dependence) are obtained for the residual pressure of 500 mbar. Comparison of the data with a linear fit for this pressure level is given in figure 4.

Table 1. Correlations of the muon bundle intensity with the altitude for several fixed pressure levels. Indicated errors of regression coefficient are statistical.

P_L, mbar	<*H*>, km a.s.l.	R_H	β_H, %/ 10 m
100	16.07	- 0.850	- 0.1324 ± 0.0014
300	9.08	- 0.956	- 0.2016 ± 0.0019
500	5.53	- 0.971	- 0.3067 ± 0.0028
700	2.98	- 0.947	- 0.4477 ± 0.0042
900	0.99	- 0.746	- 0.4940 ± 0.0059

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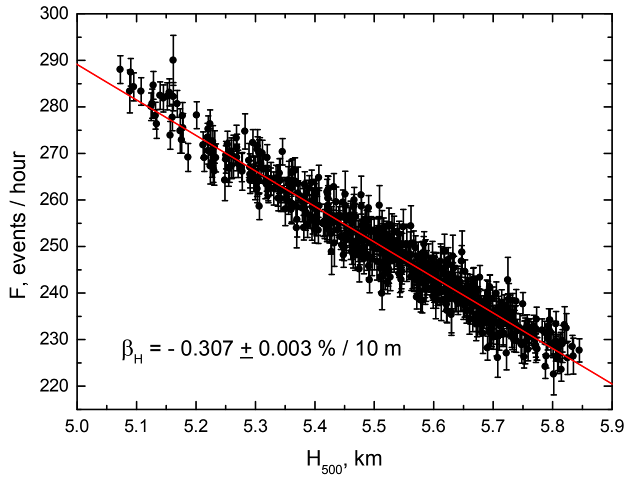

Figure 4. Correlations of the event rate with the altitude of the 500 mbar residual pressure level. Line: linear fit defined by equation (2).

5. Geometrical mechanism of muon bundle intensity variations

Taking into account that the energies of muons in the bundles are of the order of tens GeV, the observed values of barometric and temperature coefficients cannot be explained by a usual mechanism of absorption and decay of low energy particles, typical for single muons detected at the ground level [6]. An alternative approach to interpretation of the variations in the muon bundle intensity was suggested in [3]. Detection of the bundles with a detector, which is small compared to the lateral size of EAS in muon component (of the order of few hundred meters at the ground), corresponds to selection of events according to the local muon density *D*. Under some simplifying assumptions, the integral local muon density spectrum may be estimated as [4]:

$$F(\geq D) = N_0 D^{-\beta} \int [\rho(E_0, \mathbf{r})]^{\beta} dS \quad , \tag{3}$$

where $\rho(E_0, \mathbf{r})$ is the lateral distribution function (LDF) 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 β is the spectrum slope.

Changes in the effective altitude of muon bundle formation *H* relative to the mean value $<H>$ lead to a scaling geometrical transformation of the muon LDF, and the intensity (3) will follow the law $F \sim (<H>/H)^{\alpha}$, where $\alpha = 2(\beta - 1)$. An illustration of the influence of the temperature of the atmosphere on the muon LDF is given by figure 5.

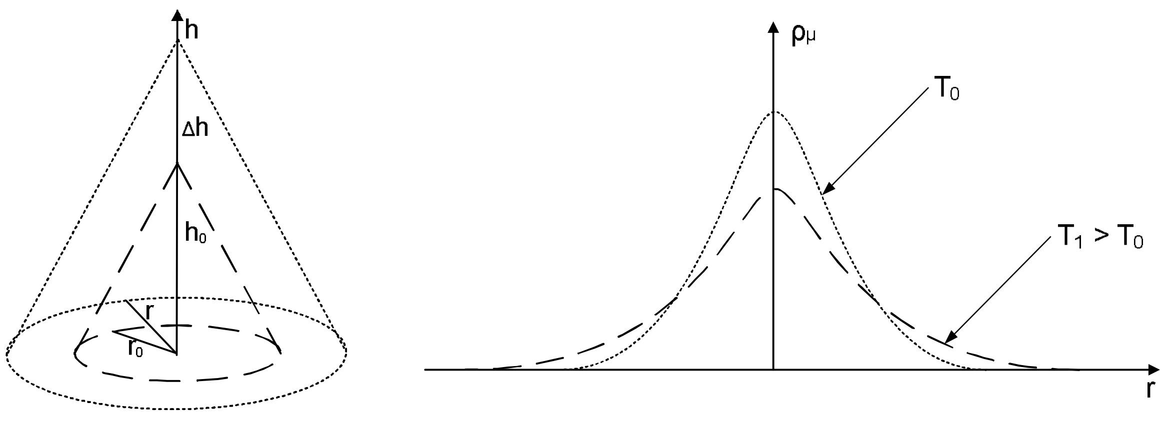

Figure 5: Illustration of the increase of the radial spread of muons (left) and of changes of the lateral distribution function of EAS muons (right) at the heating of the atmosphere [3].

For a fixed pressure, the geometrical altitude is proportional to the temperature, therefore we may expect the temperature dependence as $F \sim (<T>/T)^{\alpha}$. On the other hand, for a constant temperature, the altitude of a fixed pressure level P_L varies with the pressure at the ground P as $H \sim \ln(P/P_L)$, and assuming that the bundles are formed at altitudes corresponding to a residual pressure P_L, we obtain the expected dependence of the intensity on the ground pressure as $F \sim [\ln(<P>/P_L)/\ln(P/P_L)]^{\alpha}$. Taking into account the experimental estimate of the local muon density spectrum slope β = 1.96±0.02 derived from the muon multiplicity distribution [4], and assuming that most of the muon bundles are formed near the pressure level P_L = 500 mbar (see section 4), one can easily find the values of the variation parameters that follow from the considered geometrical mechanism (see the last column of table 2). A good agreement with the results of the experimental data analysis is obvious.

Table 2. Comparison of experimental values of the parameters describing muon bundle intensity variations with predictions of the geometrical model.

Parameter	Measured value	Geometrical model
β_P, % / mm Hg	- 0.382 ± 0.006	- 0.374 ± 0.008
β_T, % / K	- 0.760 ± 0.008	- 0.777 ± 0.016
β_{H500}, % / 10 m	- 0.307 ± 0.003	- 0.359 ± 0.007

6. Conclusion

A detailed study of the influence of atmospheric effects on the intensity of muon bundles detected at the ground level has been performed. A simple geometrical model of variation mechanism related with changes of the effective altitude of the formation of muon bundles in combination with the phenomenology of local muon density spectra explains well both qualitatively and quantitatively the observed values of barometric and temperature coefficients and correlations with the altitudes of fixed residual pressure levels.

Acknowledgments

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