Maximal possible potential difference in the stratosphere as derived from ground-based measurements of variations of secondary cosmic rays

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Annotation

Using disturbances in the intensity of cosmic ray muons, measured at different zenith angles, the electric field potential difference in the stratosphere above the observation place is determined for several thunderstorm events of the period 2014-2016. Experimental data of the Baksan Air Shower Array (BASA) of the Baksan Neutrino Observatory are used, and the analysis is based of the theory (developed earlier) of formation of muon intensity variations during thunderstorms. As a result of this analysis, the geometry of field distribution is investigated, and its average characteristics are derived.

Introduction

Energetic cosmic rays penetrating the atmosphere and generate fluxes of secondary particles. The muon component whith being born mainly in the stratosphere, reaches the ground level. According to the estimates given in [1], the intensity of muons at ground level is able to sense an electric field in a thunderstorm atmosphere. There are two mechanisms of forming variations of the total intensity (both signs of particle charge) quadratic in the field, which exert a rather strong influence (~ 1%). These are variations due to a strong nonlinear dependence of the muon decay function on energy (negative quadratic in the field effect). For horizontal, flat installations detecting muons, the contribution of the focusing action by the vertical field to the trajectory of the particles is significant. The effect is caused by a nonlinear dependence on the zenith angle of the particle detection area (positive effect on the field). Knowing the theory of the formation of muon variations, one can evaluate the characteristics of a thunderstorm field in the atmosphere.

Formulation of the problem

In [2], mean parameters of the correlation of the muon variations with the surface electric field during thunderstorms were determined by the mean characteristics of the surface lightning field. For example, it was found that the reason for the limitation of the surface slowly varying voltage during thunderstorms, in the region of ~ 10 kV/m, is a runaway breakdown at zero isotherm altitude (3-4 km above sea level in summer). At the same time, the corresponding characteristic breakdown strength in units of overvoltage (in units of critical strength D = 216 kV/m under normal conditions in air) is δ = 2.4-2.9. Investigating the "anomalous" perturbations of the intensity of muons recorded during thunderstorms and not statistically related to ground-level intensity, we can determine the energy transferred to the muons by the thunderstorm field.

Method

It is known that the total resistance between the ionosphere and the earth's surface is 230 Om, which provides a total potential difference of 0.2 MV. Figure 1 shows a modern representation of the characteristic electrical structure of a mature thunderstorm cloud.

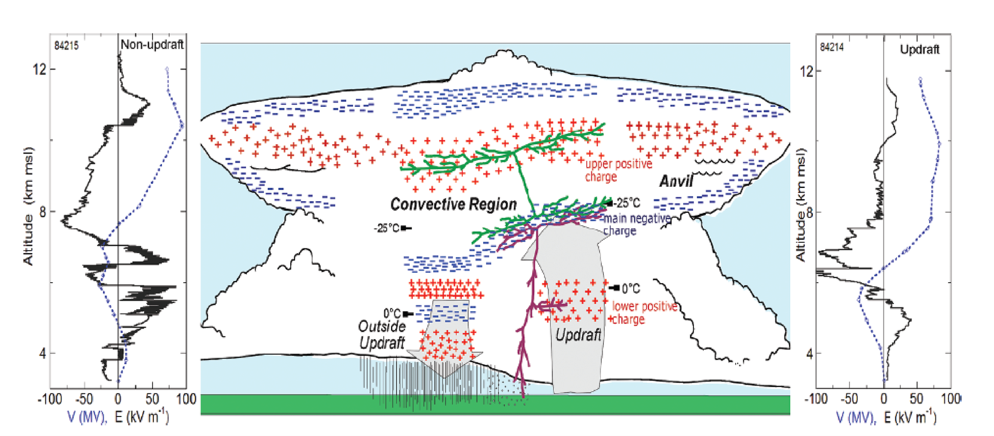

Fig.1. A modern representation of the electrical structure of thunderstorm cloud.

Although locally, the intensity can reach a critical value for breakdown on runaway electrons (~ 300 kV / m under normal conditions), but differs by a rapid change of sign, so that the potential difference varies slowly, and the higher - the more stable. Using these data, a more accurate estimate of the upper level of the field potential difference measured from the variations of muons is made, it is determined by the muon sensitivity limit to the influence of the electric field. In the upper layers of the atmosphere, the muons are just multiplying - they are few, the energies are high - the nonlinear contribution of the decay function is not great, all this forms a region of low sensitivity. The level of its lower boundary depends on the energy registered by the muon facility. For our setup recording muons at a level of 840 g/cm^2 with a threshold of 100 MeV, the lower boundary of this region is t* = 83 g/cm^2 (17.1 km), for muons with an energy of 1 GeV: t = 167 g/cm^2 (13 km) .

Thus, measuring the difference in potentials in the atmosphere between the "sensitivity level to the influence of the field" and the earth's surface by measuring "anomalous" perturbations of muons, we determine the field in the stratosphere. From the maximum observed value of this quantity, knowing the size of the region of low sensitivity, one can determine the characteristic average field strength in the stratosphere. This is the purpose of the work.

Description of the facility

The Baksan Air Shower Array (BASA) is located in a mountain valley of North Caucasus 1.7 km above the sea level. Nearby mountain peaks on both sides of the valley both have altitudes of about 4 km a.s.l., being located at distances of approximately 5 km. In the experiment studying variations of different components of cosmic rays during thunderstorms, in addition to counting rates of particles, the atmospheric pressure, temperature, near-ground electric field strength, and precipitation electric current are permanently recorded. The detected particles are divided into soft and hard components. As a result, two independent channels of secondary particles of cosmic rays, probing the atmosphere, are experimentally isolated.

Description of the experiment

In [3], statistical analysis of the amplitudes of anomalous perturbations has already been carried out, but this material has integral characteristics with respect to the zenith angle. In principle, the mechanism of focusing particles recorded at an angle can be taken into account, but it is difficult to do this with sufficient accuracy. Complication is caused by the tilt-amplifying effect of the unknown azimuthal distribution of the spatial inhomogeneities of thunderstorm fields. Therefore, to determine the characteristics of the limiting effect of the thunderstorm field on the intensity of muons, it is convenient to consider the variations of vertical particles. In [4], a description is given of the experiment carried out on the BASA facility of the BNO of the Institute of Nuclear Research of the Russian Academy of Sciences on registering variations during thunderstorms of the intensity of inclined muons. The essence of the method is that when recording with an facility composed of a continuous horizontal layer of scintillation detectors, more inclined muons give a larger signal. This allows us to determine four independent parameters by dividing the entire energy release region of muons (more than 30 MeV) into four equal parts in the count rate (Fig. 2).

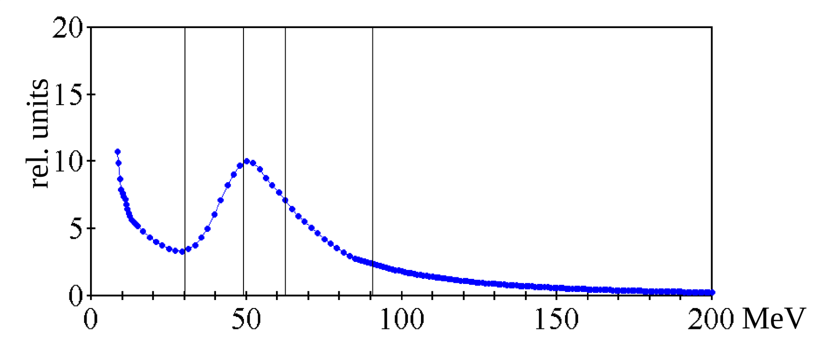

Fig.2. The spectrum of registered muons with fission in equal parts by intensity. The fissions with some accuracy correspond to the different directions of registration of muons. The first part - a soft component, the second and third parts - from 0 to 37 , the fourth - from 37 to 57 , the fifth - from 57 and above. The first part contains mainly the electron-photon component, it is cut off by the position of the threshold characterized by the greatest stability (30 MeV) in this experiment it is not used.

Taking into account the correction, the breakdown of the intensity of the detected particles by energy release gives information on the variations in the three ranges of the zenith angle: 1) 0 - 37 , 2) 37 - 56 , 3) 56 - 65 . The approximate size of the scanned areas is shown in Figure 3.

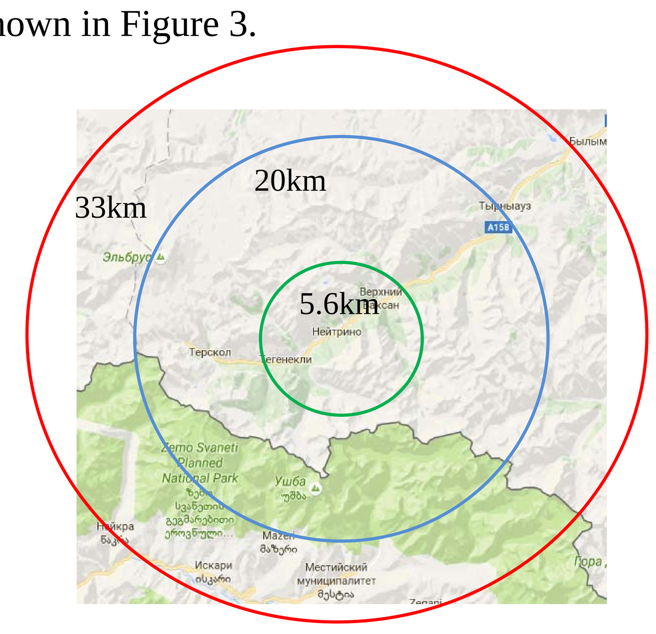

Fig.3. Areas of the atmosphere of cylindrical shape viewed through the muon sounding method are shown in the BASA facility, in accordance with the established registration thresholds (37 ⇔ 5.6 km, 57 ⇔ 20 Km, 65 ⇔ 33 Km). View from above.

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In [5], an example of a specific event describes the procedure for obtaining an estimate of the potential difference in the stratosphere. In this paper, according to the material of the year 2015, the statistics of anomalous perturbations of the intensity of muons registered by the facility at different zenith angles were collected. The difference in the potentials of the atmosphere field above the facility was determined from the regression equation for the anomalous perturbations described in [1]:

$$100\% \cdot \Delta N_a / N_a = A_a \cdot \Phi_a + B_a \cdot \Phi_a^2$$

Here, N_a is the intensity of the muons detected by the detector in the region of the maximum energy release (30-63 MeV). This group corresponds to the registration of vertical particles in the zenith angle range of 0-37o. The values of the coefficients in the equation for this angular range are calculated on the basis of the results of the work listed above. The specific value of the coefficients: A_a = 2.8 (1 0.04)·10^{-3} [%/MV], B_a = -9.8 (1 0.37)·10^{-6} [%/MV^2]. In parentheses, methodological calculation errors are given.

Results

During the processing of information, lightning events were selected that satisfied the requirements of stable operation of the equipment. Also, the presence of an anomalous perturbation of the soft component was required, which indicates the passage above the facility of the active region in the thunderstorm event. Since, in principle, during generation of thunderstorms, generation of photons with an energy of more than 30 MeV recorded with muons is possible, this circumstance determined the study of only the negative potential difference in the atmosphere, which causes a stable decrease in the intensity of the muons. In this case, if the generation of photons is available, then this does not overestimate the maximum value. In addition, as a rule, photon registration is not observed during a negative anomalous perturbation of muons. For a statistically significant determination of the amplitude of perturbations of the intensity of vertical muons, information averaged over the minute intervals was used, while the standard statistical deviation was σ = 0.09%. To characterize the intensity perturbation period, the duration of its effective section was taken. The effective section was defined as a time interval, where the intensity perturbation in each minute interval exceeds half of the maximum value of this perturbation.

The results of the treatment are shown in Fig. 4.

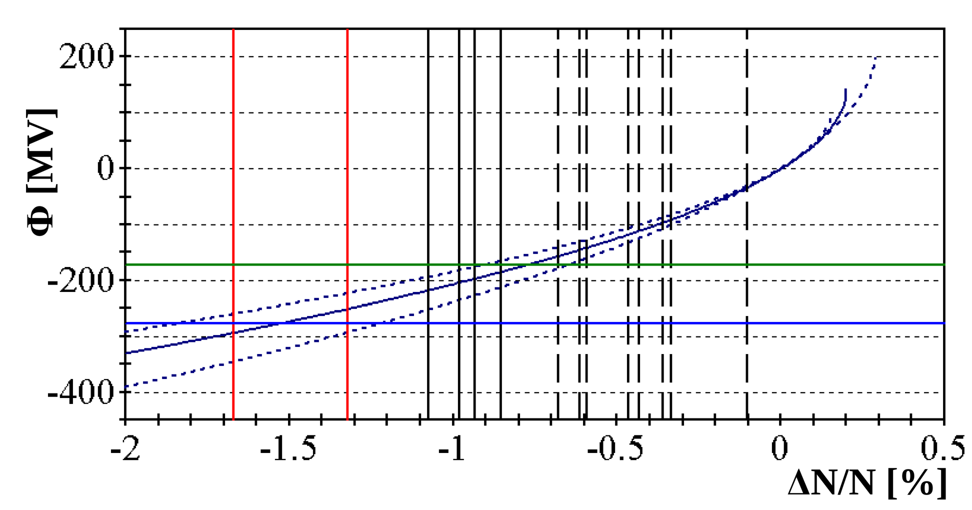

Fig.4. Dependence of the potential difference (MV) in the atmosphere measured from the level of the limiting sensitivity of muons to the effect of the field (83 g/cm^2) to the facility level (840 g/cm^2) on the amplitude of the perturbation (%) of the intensity of the registered vertical muons. The effective perturbation period is ~ 9 min. Vertical lines indicate the value of the amplitudes of specific anomalous disturbances during thunderstorms. The colored horizontal lines indicate a potential difference at different characteristic values of electrical tension in the stratosphere. Green - overvoltage δ = 1.25. Blue (lower) δ = 2.0.

Thunderstorms not accompanied by significant anomalous perturbations of secondary cosmic rays were not included in the analysis. It follows that on the statistics more than 30 thunderstorms registered for the period 2015-2016. It can be argued that the amplitude of variations of vertical muons caused by lightning fields does not exceed 2%.

An estimate of the potential difference in the stratosphere corresponding to the maximum recorded amplitude of the anomalous perturbation (-1.67%) of vertical muons has a value of 294 50 MV. The corresponding average stratospheric intensity is 2.12·(1 0.17) · Dc. Dc - the critical strength under normal conditions in the air is 216 kV/m.

Conclusions

- During thunderstorms, disturbances in the intensity of vertical muons are registered in the BASA facility of the BNO of the Institute of Nuclear Research of the Russian Academy of Sciences
- The negative perturbation amplitudes are limited to -2%
- According to the calculation, this amplitude corresponds to the establishment of a maximum of the potential difference of 294 (1 0.26) MV in a region of 83 g/cm^2 in the upper part of the atmosphere
- In this case, the average field strength in units of overvoltage δ = 1.57-2.7, which corresponds to the breakdown condition for runaway electrons.