Variations of cosmic ray muon flux during thunderstorms as a tool for studying electric field distribution and particle production processes in the atmosphere

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Abstract. The recently published result of GRAPES-3 (a strong thunderstorm muon intensity change) and conclusions made on its basis by this collaboration are discussed and compared with the Baksan observations of muon variations during thunderstorms performed much earlier. It is demonstrated that generally both experiments are quite consistent as far as characteristic patterns of events are concerned, as well as conclusions about direct connection between amplitude of muon intensity disturbance and electric field strength in the atmosphere. However, the GRAPES-3 conclusion about gigavolt potentials associated with their event is doubtful and seems to contradict the fundamental limits on electric fields that can exist in the atmosphere.

1. Introduction
Galactic cosmic rays interacting with air atoms generate the permanent flux of many generations of secondary particles propagating deep into the atmosphere. This “equilibrium” flux is subject to variations associated with weather conditions (barometric and temperature effects). During thunderstorms the strong electric fields of thunderclouds form a very specific source of disturbance. The most abundant charge particles (electrons, positrons, and muons) are accelerated or decelerated depending on the field polarity and particle’s charge sign. Variations of secondary cosmic rays during thunderstorms were first proved to be related to the strong electric field (measured near the ground surface) in a pioneering experiment carried out by A.E. Chudakov with collaborators in early 1980s (for references see [1]). The new version of the same experiment [2, 3] yielded a lot of data on variations of cosmic rays during thunderstorms, and several other experiments are studying these phenomena too. The theory of electron runaway breakdown [4] seemed to be a natural basis for interpretation of experiments in this field. However, some peculiarities of enhancements of the soft component of cosmic rays (electrons, positrons, and gamma rays with energy 10-30 MeV) recorded in [2, 3] excluded simple explanation using this theory and required to suggest a new mechanism responsible for observed events. In order to explain experimental data, a mechanism of generation of elementary particles by thunderclouds was suggested in paper [5]. The essence of this mechanism is formation of a feedback loop in strong electric field: in one and the same field electrons are accelerated in one direction and positrons in the opposite direction. The process of pair production with subsequent Coulomb scattering turning back one component of the pair (moving against the
accelerating field) closes the positive feedback loop resulting in exponential increase of particle intensity in a limited volume.

2. GRAPES-3 event and muon effects during thunderstorms as measured by BASA

The GRAPES-3 collaboration recently published [6] a single event of outstanding decrease of the intensity of 1 GeV muons during a thunderstorm (Fig. 1). Before comparing this result with those obtained in the Baksan experiment in more detail, we would like to demonstrate the brightest event of muon variations in our experiment (Fig. 2). The deviation of muon flux from its mean value presented in the middle panel of Fig. 2 has the amplitude close to the maximum (muon effects exceeding 1% practically never observed), but its duration is unusually large: typical events are much shorter, with a mean duration of about 8-10 min. The reason why just this event is selected for comparison is the very clear signatures of lightning effects. Lightning discharges are well seen by both electric field meter (top panel) and precipitation electric current recorder (bottom panel). In thunderstorm beginning two arrows show two jumps of muon intensity coinciding with lightning strokes. Recovery to the undisturbed intensity level is rather slow, about 5 min (compare with electric field recovery lasting some seconds).

Fig. 1. The GRAPES-3 maximum muon intensity variation $\Delta I_{\mu} = -2\%$, starting at 10:42 Universal Time (UT) and lasting 18 min, seen during thunderstorm of December 1, 2014. The plot is taken from paper [6].

Fig. 2. Baksan maximum event on September 24, 2007 with anomalously long duration and several lightning effects. Top and bottom panels present near-ground field and precipitation electric current.

Fig. 3. Muons with $E_{\mu} > 100$ MeV, deviation from the mean intensity as a function of near-ground electric field strength (weighted average curve, summation over separate thunderstorms). Solid circles correspond to distribution after exclusion of $\pm$ 300-second periods of active thunderstorm phase (no lightning discharges nearby). One can see very regular behavior within $\pm$ 7 kV per meter interval, irrespective of lightning activity.
After strong reduction of muon intensity another pair of lightning discharges produces the opposite effect: quick jump to the undisturbed level with equally slow recovery to depressed intensity. The picture of Fig. 2 is extremely important in one respect: this is the only direct proof that transient muon variations are really induced by the electric field: no other factor (like pressure, temperature etc.) can make so quick changes. There is one remarkable difference between the events in Figs. 1 and 2: the amplitude in the first case is twice larger.

Taking into consideration that the data of Fig. 2 present the flux of muons with energy threshold of 100 MeV and the fact that, according to Baksan results [7, 8], the amplitude of muon effects (quite naturally) drops down with increasing energy threshold, this difference becomes even more significant.

Now let us describe in short the main results obtained by BASA on muon variations during thunderstorms. Figure 3 presents deviation from the daily mean intensity of 100 MeV muons as a function of near-ground electric field strength (weighted average curve, summation has been made over separate thunderstorms). The solid circles in the figure correspond to the same distribution after exclusion of ± 300-second periods of active thunderstorm phase (to eliminate effects of even distant lightning discharges). This function is well described in the interval ± 7 kV per meter by a second-order polynomial. Presumably the quadratic term is caused by symmetrical process of decays of muons of opposite signs, while the linear term is obviously connected with a large excess of positive muons. In addition to this regular behavior many bright muon events similar to those shown in Figs. 1 and 2 were detected in the Baksan experiment. Statistical properties of variations in cosmic ray muons during thunderstorms were analyzed in paper [9].

In order to describe the thunderstorm muon effects a certain theoretical analysis of muon propagation in atmospheric electric field during thunderstorms was started in [8] and continued in [10]. Based on correlations with the near-ground field (Fig. 3), estimates were made of regression coefficients with the mean potential difference in the stratosphere, between the effective level of muon production and the ionosphere. It is shown that maximum observable muon effects (variations with amplitudes of 1%) correspond to a mean potential difference in the stratosphere of about 200 MV. It should be noticed also that the long investigations of cosmic-ray variations during thunderstorms have shown that a variety of effects can be observed during thunderstorms. There were the soft component enhancements (later called TGEs), without muon effects. They have larger
amplitudes and relatively small altitudes of production. Smaller amplitude enhancements can have their origin at extremely high altitudes and be accompanied by muon variations (both negative and positive are possible), like in the event of Fig. 4. Purely muon effects (the case of Fig. 2) are also possible. There are other effects observed during thunderstorms by BASA and in some ways connected with cosmic ray effects (geomagnetic pulsations, high-altitude glow above thunderclouds), but here we deal only with electric field measurements.

3. Discussion and conclusions
GRAPES-3 and BASA are very convenient arrays for comparison. First of all, their altitudes above the sea level are rather close: 2200 and 1700 m a.s.l. The energy thresholds for muon detectors are equal (1 GeV), though the BASA data were predominantly analyzed for 100 MeV threshold (the amplitude of thunderstorm muon effects is larger at lesser threshold). The large amplitude of the GRAPES-3 muon event (Fig. 1) is surprizing. However, when a single event is under consideration, one can suggest that some giant fluctuation is a cause of it. But even more astonishing is the unusually large potential deduced by the authors of [6] from the analysis of their event. According to the model used one gigavolt potential existed between altitudes of 8 and 10 km. Of course, regular field can exist for 2 km height, but its strength is limited due to avalanches of runaway electrons [4]. In [11] J. Dwyer deduced a fundamental limit on electric field strength in air. Instability caused by the runaway electrons is defined by the critical field directly proportional to air density. If one takes the sea level critical field value 284 kV/m [11] (probably the highest value, other estimates give slightly lower values), then at an altitude of 8 km the critical field is 144 kV/m (113 kV/m at 10 km). Even without detailed analysis of the total procedure of field reconstruction in [6] one can notice that there are some doubts about definite conclusion of authors of paper [6] about gigavolt potentials necessary for explanation of their result. If one takes the first value as a constant over 2 km height (terrible overestimation), even in this case the total potential is much less than one gigavolt.

In addition, it is worthwhile to note that in paper [10] a theoretical consideration and experimentally measured regression coefficients for muon intensity allowed a rather preliminary estimation of the stratosphere electric field to be made (200 MV for 1% of muon intensity change). Further analysis is needed to achieve proper understanding of apparent contradiction in the results of GRAPES-3 and BASA.

Nevertheless, without doubts is the fact that strong penetrating ability of muons and their effective height of generation, comparable with heights of top layers of thunderclouds, can make them a sensitive instrument for studying fields and particle fluxes in the stratosphere.

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