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Atmospheric Research 76 (2005) 346–354

ATMOSPHERIC RESEARCH

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Cosmic rays and the electric field of thunderclouds: Evidence for acceleration of particles (runaway electrons)

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Accepted 16 November 2004

Abstract

We present the data on correlations of the intensity of the soft component of cosmic rays with the local electric field of the near-earth atmosphere during thunderstorm periods at the Baksan Valley (North Caucasus, 1700 m a.s.l.). The large-area array for studying the extensive air showers of cosmic rays is used as a particle detector. An electric field meter of the 'electric mill' type (rain-protected) is mounted on the roof of the building in the center of this array. The data were obtained in the summer seasons of 2000–2002. We observe strong enhancements of the soft component intensity before some lightning strokes. At the same time, the analysis of the regression curve 'intensity versus field' discovers a bump at the field sign that is opposite to the field sign corresponding to acceleration of electrons. It is interpreted as a signature of runaway electrons from the region of the strong field (with opposite sign) overhead.

Keywords: Cosmic rays; Runaway electrons; Thunderstorms; Electric field of atmosphere

1. Introduction

The possibility of acceleration of electrons by a charged thundercloud was first discussed by C.T.R. Wilson as long ago as 1925 (Wilson, 1925). He considered the air

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0169-8095/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.atmosres.2004.11.012

from the lower atmosphere containing 'radium emanation and its products' as a possible source of electrons for the acceleration process. Since then, many attempts were made to find the predicted beams of accelerated particles (called runaway electrons by A. Eddington) during thunderstorms. A list of some experiments made in 1930–1950 can be found in Lidvansky (2003). However, these experiments made by geophysicists ignored the presence of cosmic rays and their possible role in this process. In early 1980s the experiment with the air shower array at Baksan demonstrated the obvious correlation of short variations of the intensity of secondary cosmic rays with the electric field of the atmosphere during thunderstorms (Alexeyenko et al., 1985, Alexeenko et al., 1987). Still later, (Gurevich et al., 1992; Roussel-Dupre et al., 1994) the runaway electron mechanism was suggested for air breakdown, in which secondary cosmic rays played an important part as seed particles stimulating the local discharges. One prediction of the theory is the X-ray emission associated with lightning. Some experiments made on aircraft (McCarthy and Parks, 1985), balloons (Eack et al., 1996), and on the ground (Moore et al., 2001) claimed to observe X-ray pulses associated with lightning discharges, thus qualitatively confirming the runaway breakdown mechanism. However, the role of cosmic rays in this process can be elucidated only by the simultaneous observation of their intensity. Some results of the new version of the Baksan experiment have been published recently (Alexeenko et al., 2002a). The pre-lightning enhancements of the intensity of the soft component of secondary cosmic rays were observed in this experiment. It was also demonstrated that these enhancements apparently are of two different types (Alexeenko et al., 2002b). One type has longer duration (several minutes) and is more frequent, while the other one is shorter and very rare. In addition, the relative deviation of the soft component intensity was measured versus the electric field strength, and it was shown that there were both linear and quadratic terms in this dependence. In this paper we present the same curve measured with a better accuracy: the data of three seasons of observation (instead of one) are included in the analysis. Besides, in the last season an experiment was made in order to estimate the minimum distance to lightning channels. The more accurate data and the results of this experiment allow us to suggest a new interpretation of the phenomenon we have observed.

2. Experiment

We used in the experiment the so-called Carpet-2 air shower array that includes 200 m^2 of scintillators under a roof 21 g cm^{-2} thick and 6 huts with 9 m^2 of scintillators (54 m^2 in total) with only a very thin covering. Taking ionization losses in the roof into account, the energy threshold for particles in the covered scintillation detectors is equal to 70 MeV. For uncovered scintillators two integral discriminators with threshold 10 and 30 MeV allowed us to isolate the soft component within these limits. Thus, we measured every second the hard component (E>70 MeV, basically muons) and the soft component (10–30 MeV, electrons and gamma rays), the counting rates of the components being 40000 s^{-1} and 4000 s^{-1}, respectively. In addition, the air shower array includes a muon detector (its total area and counting rate are 175 m^2 and 19000 s^{-1}, respectively) with an energy threshold of 1 GeV. The atmospheric pressure P, electric field strength D, and precipitation electric current I were also recorded every second. The electric field meter (of the electric mill type) is installed on the roof of the building. The measuring electrode in this instrument is a two-sector rotating impeller connected with the ground through the load R. Above the electrode there is an immovable screen with corresponding sector cut-outs, which allow the electrode to be unscreened for measurements. The amplitude of the variable potential on the load (proportional to the acting electric field) is measured. In order to exclude the influence of charged rain droplets the instrument includes an umbrella located above the measuring electrode and rotating together with it. The speed of rotation and the size of the instrument were adjusted so that the measuring electrode would leave the open sector before the rain droplets in their free fall could cross the distance between the umbrella and the electrode and reach the latter.

The electric mill (D-meter) was calibrated using artificially created field and its linearity was checked up to the electric field strength of 20 kV/m. Some drawback of this instrument is its inability to measure fast variations of the field because of the integration time equal to 2 s. In order to correct the data when fast variations took place we used the data of the precipitation current meter (I-meter), sensitive to the derivative of the field. A special mathematical procedure was used for this correction, so that the records of the electric field presented below are some combination of the data of the D-meter and I-meter. This procedure is not described here, since it is rather complicated. However, it is but a small correction essential only for very fast changes of the electric field.

In the last experimental runs a simple microphone system was used to estimate the distance to the lightning channels (Khaerdinov et al., 2003a).

3. Results

Fig. 1 demonstrates an example of one particular thunderstorm detected on September 26, 2001 and the effects observed in the channels recording the intensities of different cosmic ray components. Total duration of this thunderstorm is about 5 h, and the local electric field (the upper panel) is highly variable. The most prominent enhancement of the soft component (the second panel from the top) takes place immediately before a lightning stroke (coincidence with lightning is well seen in Fig. 9 of Alexeenko et al., 2002a, when the same event is presented on a small time scale) and is accompanied by a lesser enhancement in the hard component counting rate. The latter is not typical for pre-lightning enhancements: as a rule, they are observed only in the soft component. Typical effects for the hard component are intensity decreases, and some of them are well seen in Fig. 1 (the results concerning the hard component effect are discussed separately in Khaerdinov et al., 2003c). It is very interesting that even for 1 GeV muons some effect is clearly seen (for, example, at 14 h). The long-term trends observed in the two bottom panels of Fig. 1 can be explained as the effect due to changing temperature in the stratosphere (the counting rate of muons is sensitive to this temperature, and in this experiment we cannot make corrections for it).

The largest peak of the example presented in Fig. 1 was earlier published in (Alexeenko et al., 2002a) as one of the largest pre-lightning enhancements. The duration of the intensity growth before lightning is a few minutes. Another type of pre-lightning

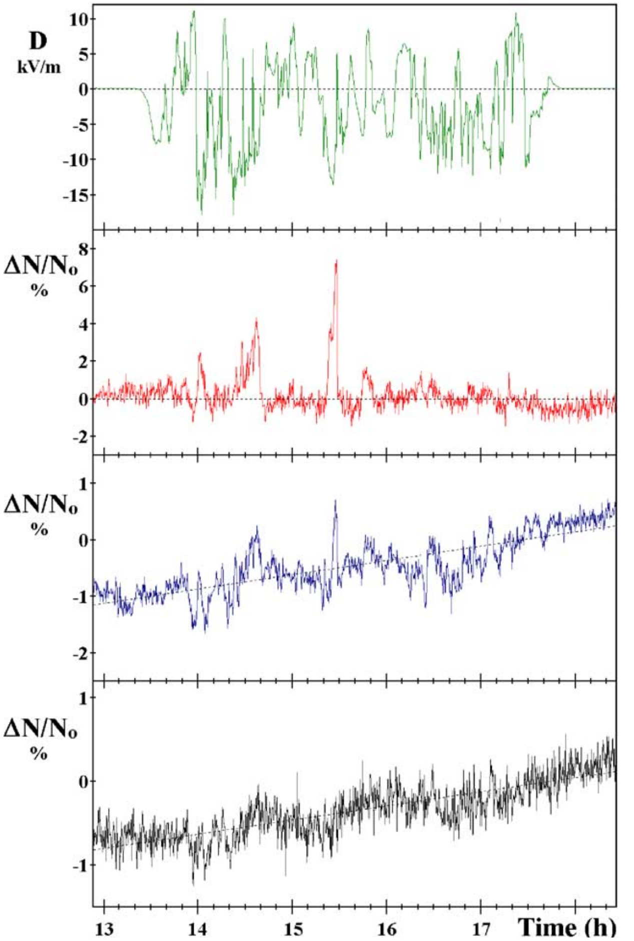

Fig. 1. Thunderstorm on September 26, 2001. The panels present the records (from top to bottom) of the electric field, the soft component, the hard component with energies of 70 MeV to 1 GeV, and hard component with energy>1 GeV.

enhancements (also published in Alexeenko et al., 2002a) demonstrated much shorter exponential increase (see Fig. 2). The exponential dependence is shown in Fig. 2 by dotted line, and the vertical dashed line marks the instant of a lightning stroke. We should emphasize that the event of Fig. 2 is apparently very rare (one event of this type was detected for three seasons of observation). The events of another type turn out to be much more frequent. Nevertheless, since the correlation of the events presented in both Figs. 1 and 2 with lightning strokes is obvious, in our previous publications we interpreted this fact as a confirmation of the theory of runaway electron breakdown.

However, in the last season we have carried out an experiment in order to estimate the minimum distance to channels of lightning events associated with cosmic ray enhancements (Khaerdinov et al., 2003a). In this experiment many enhancements of the same type

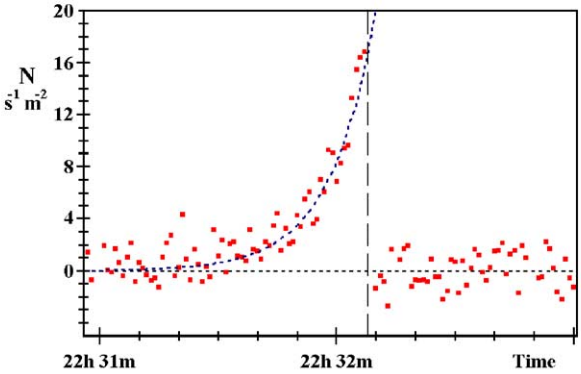

Fig. 2. Strong pre-lightning enhancement of the soft cosmic ray component during the thunderstorm on September 7, 2000, Baksan Valley. The time resolution is 1 s.

as in Fig. 1 (though not so spectacular) were detected, but all of them turned out to be associated with pretty distant lightning events. Fig. 3 gives a typical example of a short episode of the thunderstorm on August 1, 2002. There are three lightning events well seen in the electric field record of the top panel. (Throughout the paper, when we speak about lightning events, we have in mind similar records of very sharp fronts and subsequent slow field regeneration. They are equally well detected by the *D*-meter and *I*-meter.) Before

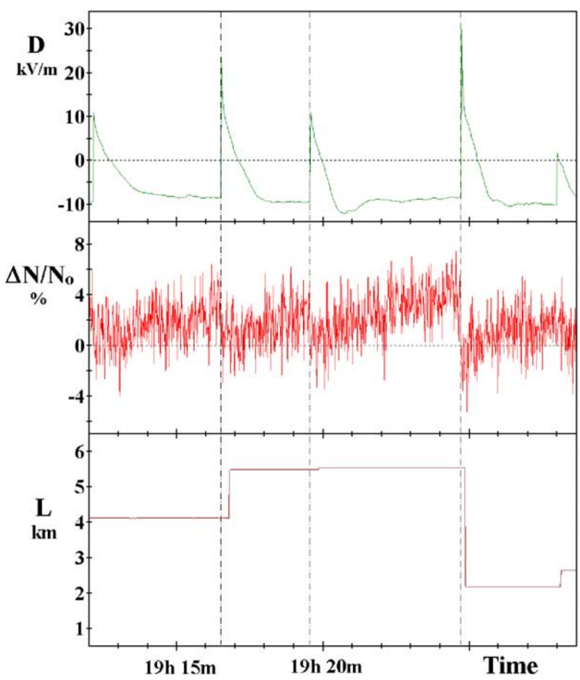

Fig. 3. A short interval of a thunderstorm on August 1, 2002 with pre-lightning enhancements of the soft component (middle panel) and minimum distances measured to lightning events (bottom panel).

each of them the counting rate of the soft component (middle panel) increases. The bottom panel presents the minimum distance to these lightning events measured as described above. Note that each horizontal segment in the bottom panel represents the distance to preceding lightning (the time delays due to acoustic measurements are also well seen so that the bottom plot in Fig. 3 possesses the property of self-checking: longer delays correspond to larger distances). The total distribution of distances to lightning events is shown in Fig. 4, as well as the values of associated enhancements of the soft component of cosmic rays. The latter values were determined as differences of total counts for 20-s intervals before and after the lightning. Therefore, the standard deviation for the events presented in Fig. 4 is about 0.35%, while the maximum enhancement is equal to 4%. So, the events with rather modest enhancements detected in this run of measurements have a high statistical significance (notice that the events shown in Figs. 1 and 2 are much more significant).

The large distance to lightning channels probably means that the above enhancements are not directly related to the lightning activity. We can rather suppose that the lightning serves in our case as a switch-off for the electric field. Our experimental complex is located in a rather narrow mountain valley. The nearest mountain peak is about 2200 m higher than the observation level. The estimated distance to this peak is shown in Fig. 4 as a vertical dashed line. In Fig. 4 the mean distance to lightning is of order of this distance, while the majority of events fall within the limits between 2 and 5.5 km. The conclusion about the absence of direct association with lightning events sets us to look more attentively at the correlations of all data with the electric field strength.

We first analyzed the correlation curve 'intensity versus field' in (Alexeenko et al., 2002a) using the data of one observation season. Now the full analysis of the data of

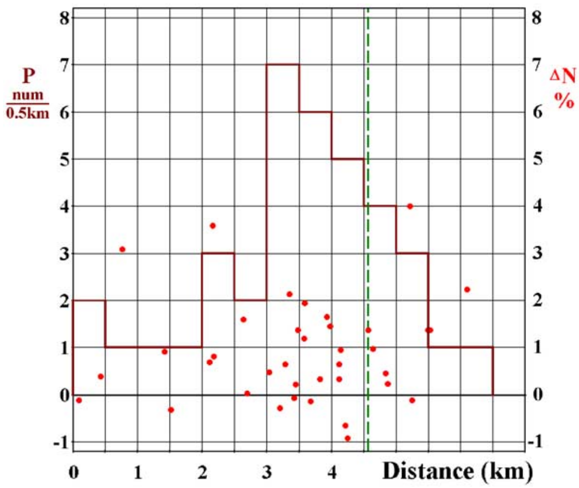

Fig. 4. Distribution of minimum distances to lightning channels (histogram and left scale) measured in the season of 2002. The increases for individual events are shown by points (right scale). Distance to a nearby mountain peak is shown by vertical dashed line.

three seasons of observation is accomplished. The total number of thunderstorm events detected in these three seasons (2000–2002) is 108. Since the effect under study is very small (the linear term in our regression curve below is approximately 20 times lower than the corresponding barometric coefficient) and masked by many spurious effects during thunderstorms, we applied a special procedure of filtering the data and checking their homogeneity. In order to filter the data, we have used the ratio of odd and even huts containing the soft component detectors. The procedure of filtering is shortly described in Khaerdinov et al. (2003b), as well as further processing with optimization of the data sample. The final result of this analysis is shown in Fig. 5, where only 52 thunderstorm events that survived all homogeneity tests and optimization procedure are included.

The solid curve in Fig. 5 is the weighted mean of approximations by second-degree polynomials made in each thunderstorm event. The form of this curve is quite understandable. Its left branch corresponds to the process of acceleration of electrons (all electrons of secondary cosmic rays gain additional energy in the electric field so that their counting rate increases at a constant threshold of detection). Similarly, the right branch of the curve of Fig. 5 corresponds to the acceleration of positrons in the field of the opposite sign. The asymmetry of the curve is due to the fact that the number of electrons is larger than that of positrons at low energies. At high energies far exceeding the critical energy in air (80 MeV) the numbers of electrons and positrons are approximately equal, and even there is some excess of positrons. However, at lower energies there are two processes that yield only electrons and no positrons: the Compton effect of gamma rays and the generation of knock-on electrons by muons and high-energy electrons and positrons.

The surprising feature of Fig. 5 is a large bump of experimental points observed in the region corresponding to the acceleration of positrons, which was expected to be less

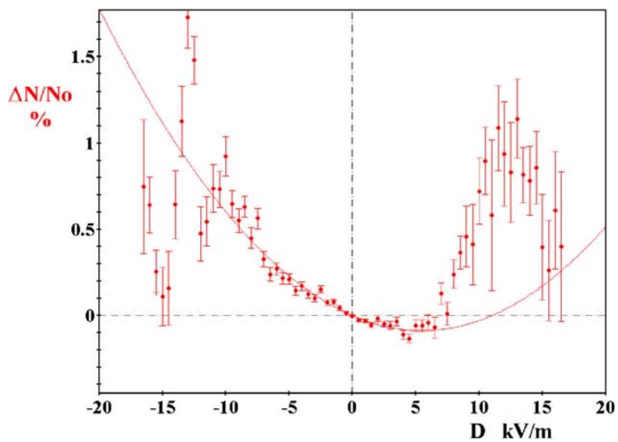

Fig. 5. The relative deviation of the soft component intensity from its average value versus the electric field strength (see text for explanation). The data include 52 thunderstorm events detected in summer seasons of 2000–2002. The bump in the right-hand part of the figure is interpreted as a signature of runaway electrons accelerated in the strong field of the opposite sign overhead.

efficient than the acceleration of electrons. This bump is very stable: it was present in our first publications where the data of only one season were included (see (Alexeenko et al., 2002a). Currently we interpret this bump as produced by electrons rather than by positrons. Near the ground we measure fairly modest field as compared to the field near the cloud layer. According to the measurements of the altitude profile of the electric field during thunderstorms (see, for example, Marshall et al., 1995), quite frequently this strong field has the opposite sign. Cosmic ray electrons can be accelerated and multiplied in this field before they go into the region of weaker field of opposite sign. In spite of deceleration and absorption, some of them have a chance to reach the observation level. Gamma rays generated by these electrons have even better chances, because they are not subject to deceleration. The detailed model calculations are necessary for final proof of this interpretation. Nevertheless, at the moment it seems to be fairly reasonable.

As was already mentioned above, our air shower array is located in a rather narrow mountain valley at 1700 m above sea level. Very close to the array a mountain slope begins with an angle of inclination of about 30°. The height of a nearby mountain peak is about 3900 a.s.l., i.e., more than 2 km above the level of observation. Hence, under these conditions, the cloud-to-ground lightning is more probable to the mountain peak and slope. Then it is probable (as we hypothesized above) that the pre-lightning enhancements such as in Figs. 1 and 3 are due to the effects of strong field of a thundercloud, which is switched off by lightning. The event of Fig. 1 is one of the most prominent, although it is essentially the same phenomenon that is seen in the average picture of Fig. 5. May be the event of Fig. 2 is much more rare event of a nearby lightning.

This situation is quite different from that taking place, for example, in the experiments where the immediate radiation of lightning (X-rays) are searched for in order to confirm the theory of runaway electron breakdown, either on balloons (Eack et al., 1996) or on the ground (Suszcynsky et al., 1996; Moore et al., 2001). It is usually believed in these papers that electrons whose energy is about 1 MeV should produce the main effect, and the pulse associated with runaway electrons must be very short. We observe the effect at the earlier stage. The typical time of pre-lightning enhancements is several minutes according to the analysis made in (Khaerdinov et al., 2003d). In addition, the energy of electrons involved exceeds 10 MeV (and can reach even several tens of MeV) in our case.

Nevertheless, in a sense, our data may give a more direct confirmation of the presence of runaway electrons than observations of secondary X-ray emission from the lightning region. In summary, we can formulate our conclusions as follows: (i) Wilson's runaway electrons do exist, (ii) their energy can be pretty high (more than 10 MeV), and (iii) they are not necessarily directly related to lightning events.

Acknowledgments

The work is supported in part by the Russian Foundation for Basic Research, grant no. 03-02-16487, and by the State Program of Support of Leading Scientific Schools, grant NSh-1828.2003.02.

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