EFFECT OF THE ELECTRIC FIELD OF THUNDERCLOUDS ON COSMIC RAYS AND EVIDENCE FOR PRE-LIGHTNING ACCELERATION OF ELECTRONS

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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 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. It is shown that at modest field strengths (within the limits of ± 6 kV/m) the soft component intensity is linear with field. At stronger fields this intensity demonstrates quadratic behavior. In addition to these effects, we observe strong enhancements of the intensity before some lightning strokes. They can be interpreted as a first direct confirmation of the runaway breakdown process, which is extensively discussed by theoreticians as a mechanism for lightning initiation. We believe that such experiments with cosmic rays can be a useful tool for studying the atmospheric electricity phenomena.

INTRODUCTION

The flux of secondary cosmic rays deep in the atmosphere is subject to variations that can be related to meteorological parameters. The disturbed electric field during thunderstorm and rainy periods is among them. The relation between disturbances in the intensity of secondary cosmic rays and the electric field strength during thunderstorms was first established by *Alexeyenko et al.* [1985]. Recently, we started a more sophisticated version of the same experiment with a higher time resolution and separating the effects for the soft and hard components of cosmic rays. Some results of these observations have been published in [*Alexeenko et al.,* 2002a; *Lidvansky*, 2003]. Here we present the refined data on the soft component including two examples of the brightest pre-lightning enhancements, which seem to be of two different types.

EXPERIMENTAL

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. The atmospheric pressure *P*, electric field strength *D*, and electric current of rain *I* were also recorded every second. The electric field meter (of the electric mill type) is installed on the roof of the building. In the last experimental runs a simple microphone system is used to estimate the distance to the lightning events.

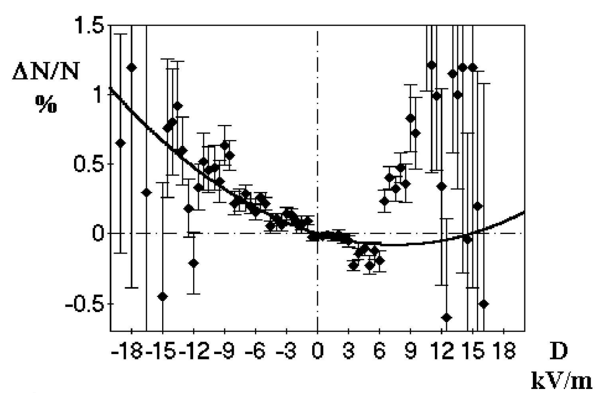

Fig. 1. The amplitude of the soft component relative variation versus the electric field strength. Observations are made at the Baksan Valley in 2000 and 11 thunderstorms are included in the analysis.

RESULTS

Figure 1 demonstrates the result already published in [*Alexeenko et al.,* 2002a]. In this paper out attention was mainly engaged by the linear behavior at the modest field strength, and we more or less ignored the strong deviations from the regression curve, assuming them to be related with irregular processes. Now we can compare these data with more detailed picture presented in Fig. 2, where the data of observations during two summer seasons are included (about 40 thunderstorm episodes with a total duration of more than 70 hours). It is evident that the linear behavior at the modest electric field strength persists as before. However, now there is some regularity in that part of data, which was previously considered as irregular. It looks like the presence of two mechanisms involved: one with linear and another with quadratic behavior.

One should take a notice that both curves of Fig. 2 represent a result of approximation by a second-order polynomial. Only the limits of approximation are different: within the range from –6 to +6 kV (the lower curve) and over the entire range of the figure (the upper curve).

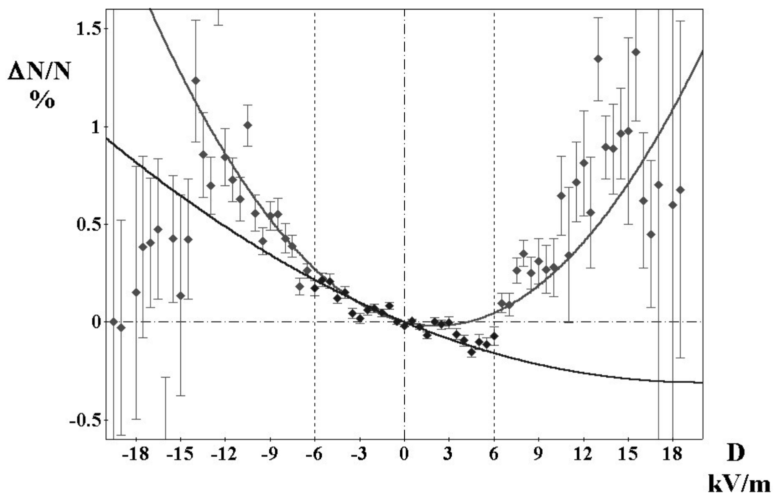

Fig. 2. The same as in Fig. 1, but with more data included (two summer seasons of observation, 2000 and 2001).

The interpretation of the data of Fig. 2 requires a detailed analysis of both the above mechanisms (linear and quadratic) and exact calculations within the framework of some particular model of the electric field distribution and energy spectra of low energy cosmic rays.

At the moment we emphasize that the following experimental fact seems to be proven: the soft component of cosmic rays enhances at any sign of the electric field. This situation is quite opposite to what takes place for the hard component (see [*Alexeenko et al.,* 2002a]).

The soft component was also found to be sensitive to some of lightning discharges. Figure 3 presents the brightest event recorded during a thunderstorm on September 7, 2000. One can see in Fig. 3 that both electric field meter (upper panel) and the meter of the electric current of rain (bottom panel) equally well detect lightning strokes. Before some of them there are specific increases of intensity of the soft component of cosmic rays (the second panel from the top), while practically no effect is observed in the hard component (the third panel). Of special interest is the fact that the growth of intensity is exponential up to the instant of lightning. At this instant the intensity goes down to the average level (zero level in the scale of Fig. 3). Let us remind that the exponential growth is predicted by the theory of runaway electron breakdown [*Gurevich et al., 1992*] based on the old idea of Wilson that the electric field of thunderclouds can accelerate electrons [*Wilson, 1925*]. The behavior of intensity in the largest increase of Fig. 3 is indeed exponential with high precision. Figure 4 presents this maximum separately, scaled up and fitted by an exponent.

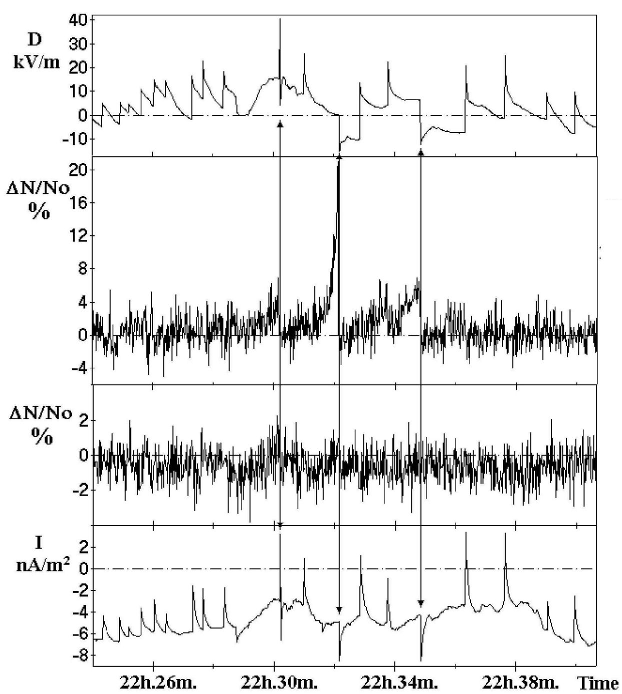

Fig. 3. Strong pre-lightning enhancements of the soft cosmic ray component (second panel from the top) during the thunderstorm on September 7, 2000, Baksan Valley. The time resolution is 1 s.

It is worth noting that the event of Fig. 3 is, apparently, rather rare in our experimental conditions. More frequent are the events of pre-lightning enhancements of a somewhat different type. This second type (the brightest example was detected on September 26, 2001 and presented in [*Alexeenko et al.,* 2002a]) is characterized by a slower increase of the intensity: its total duration is five minutes instead of half a minute in case of Fig. 3. The time properties of this event can be seen in Fig. 5, where the vertical dashed line marks the instant of lightning. Perhaps, the most interesting fact is that the events of the first and second types are associated with lightning of different polarity [*Alexeenko et al.*, 2002b]. It is also important that the energy spectra of particles seem to be different for the events of different types. This is well seen in Fig. 5, where two curves represent the data for the soft and hard components. Unlike the event of Fig. 3, there is a considerable effect in the hard component in the case of the event of Fig. 5.

DISCUSSION

The refined data of Fig. 2 confirm earlier evidence that the intensity of soft cosmic ray component is linear with the electric field up to strengths of about 6 kV/m. At stronger fields, the quadratic behavior seems to take place, which is, apparently, associated with another mechanism.

As for the pre-lightning enhancements of cosmic ray intensity, they are obviously of at least two different types. Figures 4 and 5 illustrate the basic features of these types: in one case exponential growth with a soft energy spectrum, and in another case much longer enhancement with obviously much harder spectrum.

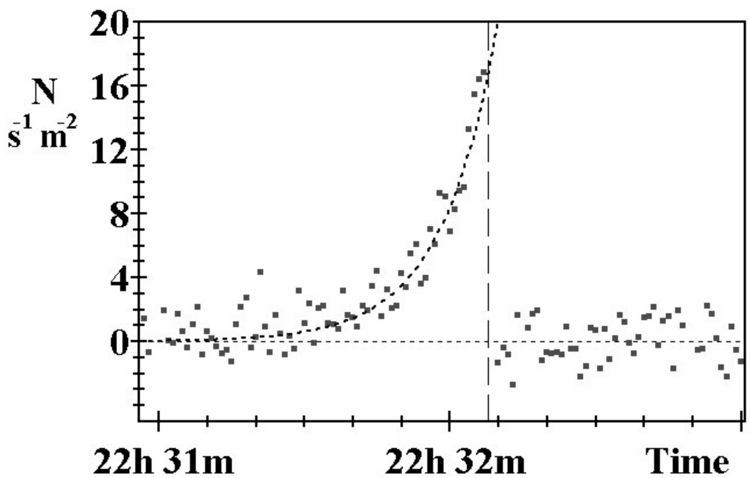

Fig. 4. The detailed profile of the largest increase in Fig. 3. The number of excess counts are plotted versus time, and the instant of associated lightning is shown by the vertical dashed line.

The largest increase of Fig. 3 is equal to 20% of intensity. The effect is highly reliable from the viewpoint of statistics: at least 20 points show statistically significant excess, the largest one being as high as 13 standard deviations (σ = 1.5%). This largest increase is also remarkable by its precise exponential character. When its profile is approximated by the formula

$$\frac{\Delta N}{N_0} = A \cdot \exp\left(\frac{t - t_0}{\tau}\right),$$

the e-folding value is $\tau = 11.4 \pm 0.1$ s. This type is perhaps rather rare in our experimental conditions, since it is still a single evnt of this type recorded.

The events like that of Fig. 5 are more frequent: we have recorded several such events, of which the event of Fig. 5 is the brightest. For this event we can draw some conclusions about the nature of the additional component detected. Our scintillators are sensitive to charged particles, gamma-rays, and neutrons. Since no identification of particles is made in the experiment, one can suggest that, for example, the high flux of neutrons causes the effect. However, since the additional radiation penetrates through the roof, we can evaluate its absorption coefficient. It turned out to be equal to 31.8 ± 1.3 g/cm^2, which is rather close to the value experimentally determined for the regular soft component in our particular conditions (34.9 g/cm2). Thus, most probably, before the lightning we detect the same electromagnetic radiation with approximately the same spectrum (one cannot also exclude a certain small contribution of neutrons).

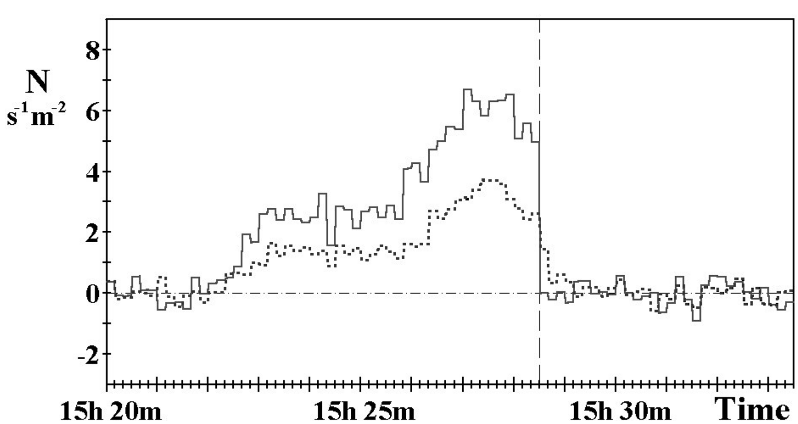

Fig. 5. The event of pre-lightning enhancement on September 26, 2001. The lightning instant is shown by the vertical dashed line. In these event the effect is observed not only in the soft component (solid line), but in the hard component as well (dotted line). The data are averaged with a bin width of 10 s.

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. We can then hypothesize that we regularly observe the effects of strong field of a thundercloud, which is switched off by 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]). We believe that our data are mainly concerned with the strong field effects, since the estimated minimum distance to lightning channel is rather large: on the average 2-5 km (these data will be published elsewhere). May be the event of Fig. 3 is more rare event of a nearby lightning.

In a sense, this may be a more direct confirmation of the presence of runaway electrons than observations of secondary X-ray emission from the lightning region. Taking our energy interval into account one can state that the energy of these runaway electrons can be fairly high (up to several tens of MeV). In addition, if our interpretation is valid, the large duration of both above events (Fig. 4 and Fig, 5) perhaps indicates that the conditions for generation of runaway electrons can exist for a rather long time.

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