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A Strong Enhancement of Cosmic Ray Intensity during Thunderstorm: A Case Study and Implications

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A very spectacular event of enhancement of the soft component of secondary cosmic rays was detected by the Carpet air shower array at Baksan Valley (North Caucasus) during a thunderstorm on October 11, 2003. The maximum amplitude of the effect reaches 30% increase above the background level for the energy range from 10 MeV to 30 MeV (absolute record for several seasons of observation). For the first half of this range the increase of counting rate is even as large as 40%. The regular profile of the enhancement demonstrates an exponential growth with saturation and then a longer exponential decay. A remarkable feature of the event is two interruptions of this regularity both on the leading and trailing edges of the profile which are obviously related to two lightning discharges detected by the electric field meter. An interpretation of the event is given in the context of a possible scenario of the involvement of cosmic rays into the dynamics of the thunderstorm atmosphere. The feedback cycling acceleration of charged particles in the thundercloud electric field is a key process in this scenario.

1. Introduction

The variations of cosmic rays during thunderstorms were first proved to be related to the strong electric field measured near the ground surface in a pioneering experiment headed by A.E. Chudakov [1, 2]. In recent years this experiment is being continued [3, 4] and a large body of experimental data obtained allows us to make some conclusions about real mechanisms of mutual influence of electric field strength and cosmic ray intensity. Correlations with the electric field were experimentally studied both for the soft [5] and hard [6] components of secondary cosmic rays. The results for the soft component include (i) very bright events of pre-lightning enhancements of the counting rate and (ii) regular variations of the counting rate correlated with the near-earth electric field of the atmosphere in a rather peculiar way. Most likely, both these group of data represent one and the same phenomenon which we tried to interpret in the context of the runaway air breakdown theory. The very bright event discussed in this paper represents a new piece of data which, in our opinion, can provide for better understanding of the experimental and theoretical situation.

2. Experimental Data

The time profile of this outstanding event is shown in Figure 1. Counting rate of scintillators (total area is 54 m^2) located under a thin roof (1 $g \cdot cm^{-2}$) in the energy range from 10 to 30 MeV is presented in the upper panel with 1-s time resolution. The lower panel presents the electric field strength also measured every second. As is seen, the electric field meter clearly detects lightning events.

First of all one should notice that the amplitude of this enhancement (30%) is absolute record for several years of observation. It is interesting that it can be even higher if lower energies are involved. For the sake of uniformity Figure 1 presents the data for the same interval (10-30 MeV), as for earlier published events. However, for particles in the energy range from 10 to 14 MeV the amplitude of enhancement exceeds 40%.

This event is interesting not only by its prominent value. As some of previously reported examples, it also demonstrates clear correlation with lightning. The initial exponential increase interrupted at the instant of a lightning stroke (360th second) looks very similar to a 20% increase during thunderstorm on September 7, 2000 discussed in [3, 4]. However, unlike the previous case, after an interruption at the instant of lightning, a new increase fully develops and reaches, probably, its natural saturation. After the maximum increase, an exponential decay (slower than the increase) occurs, and it is also interrupted by another lightning.

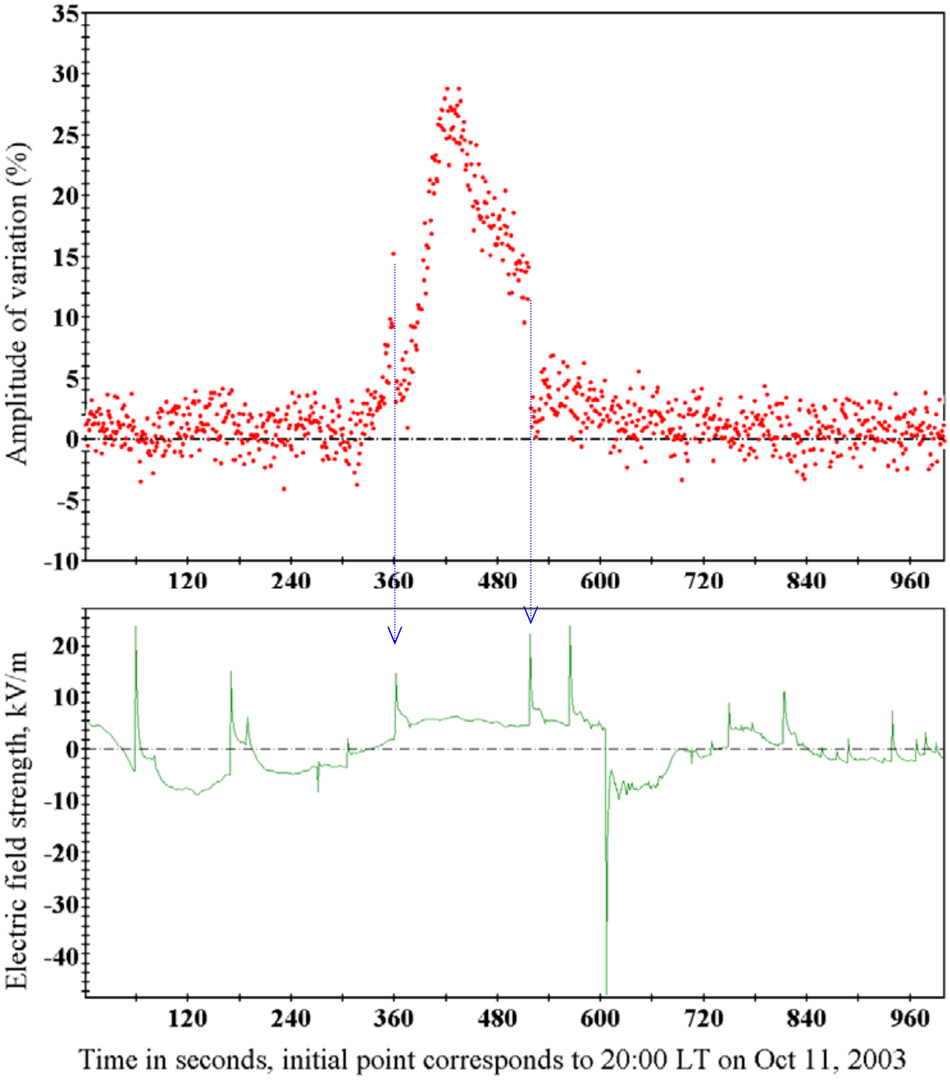

Figure 1. The great enhancement detected during thunderstorm on October 11, 2003. One lightning discharge stops the exponential increase, and another one terminates the slower decay of the intensity.

Both lightning strokes making so big effects in Figure 1 are rather distant (4.4 and 3.1 km, respectively). It is also of special interest that another lightning which occurs soon after the 600th second has no effect altogether, while it is probably very close, a few tens of meters.

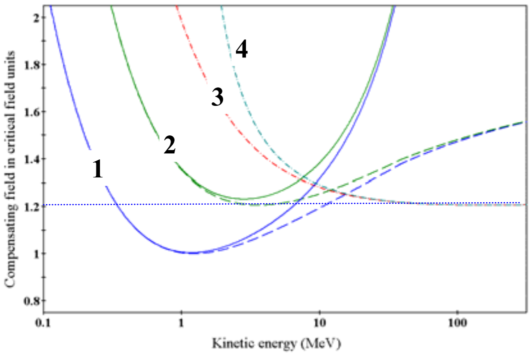

Figure 2. Admissible regions of the runaway and feedback processes in the electric field. See text for explanations.

The structure of this event confirms the conclusion made on the basis of an analysis of the intensity-field correlation [4]: there are intensity variations of particles during thunderstorms that cannot be ascribed to mere transformation of their energy spectrum in the electric field. The production of new particles is required. Presumably, this production takes place in the region of much stronger field (in comparison with the field near the ground) in the cloudy layer. The height of this layer is no less than 4 km above the level of observation. The absorption coefficient determined according to attenuation in the concrete roof (21 g·cm^{-2}) above the central Carpet of scintillators [3] turned out to be equal to 35 g·cm^{-2}. With this absorption factor the 30% increase of intensity should correspond to the intensity increased by many orders of magnitude at the level of particle generation.

3. Model for production of particles by thunderclouds

According to the theory of runaway air breakdown [8, 9], runaway particles originate when their energy losses in medium (air) is compensated by acceleration in the electric field. The relativistic runaway electron avalanche is characterized by the critical field and characteristic length. Recent Monte Carlo calculation has shown [10, 11] that the critical electric field (the threshold for runaway process) in air is larger by 25% than that corresponding to minimum ionization losses. We have considered, in the context of elementary theory, the process of particle motion in the electric field, with regard to multiple Coulomb scattering. Derivation of equations and their solution are too cumbersome to be presented here, so only the results are presented (Figure 2) and discussed. Curve 1 in Figure 2 shows the energy lost by a particle (ionization without bremsstrahlung is shown by a dashed curve, while the solid curve represents full energy losses) in the units of standard critical electric field (216 kV/m at sea level). When multiple Coulomb scattering is neglected, in a constant electric field this curve serves as a separatrix between the regions where runaway process is possible and forbidden. If one takes multiple scattering into account, curve 2 represents the results of estimation of the minimum field at which the runaway process is possible. According to curve 2, the critical field is 24% higher than for curve 1 (compare with 25% obtained in Monte Carlo calculation [10]). The important fact for us is that the energy of particles involved in the runaway process is considerably higher than in case of curve 1. Now, for higher energies the bremsstrahlung process becomes significant. A runaway particle can emit a photon. If the photon energy is sufficiently high, it has a probability to produce an electron-positron pair. One particle of this pair (of the same sign as the original particle) continues the acceleration in the field, while another one is subject to deceleration and scattering. With a certain probability the multiple scattering can turn it by an angle of 180°. In this case, this particle (positron) becomes a runaway particle, but in the opposite direction.

The entire above scheme of reasoning is valid for it, and after acceleration with similar interactions this positron can finally produce electron becoming runaway along the original electric field. In this way one can obtain additional flux of runaway electrons, and a feedback arises. Curves 3 and 4 in Figure 2 illustrate the results of calculation for the conditions of origination of this feedback process. Curve 3 represents the threshold kinetic energy of a particle which is capable of turning back in a decelerating field and becoming a runaway particle. Curve 4 corresponds to the estimated minimum energy of a particle capable of producing a pair of particles one of which subsequently turns back and is involved in the runaway process. The feedback process is allowed between curve 4 and the right branch of curve 2. The minimum of the allowed region corresponds to energy of about 10 MeV and to a field of about 1.3 critical fields.

4. Discussion

The presence of feedback means an exponential growth of particle intensity under steady-state conditions. Since the probability of the process described above is very low, this growth can be sufficiently slow and it can explain the experimental data, both presented in Figure 1 and published by us earlier. The first exponential increase in Figure 1 is terminated at the instant of lightning. This is obviously due to the fact that the process is sensitive to field variations: the lightning stroke causes temporary field redistribution, and the conditions for feedback cycling are violated for a moment. However, the general field structure remains stable, and the exponential growth starts again. Strong increase of the intensity of generated particles causes additional ionization and, accordingly, electric currents that limit the field thus stopping further multiplication and stabilizing the process. So, this feedback cycle can be essential and even the main process of regulation of the electric field in the atmosphere.

Up to now the avalanches of runaway electrons were considered as a factor setting the fundamental limit on electric fields in air [10]. Indeed, one can see in Figure 2 that the critical field for existence of runaway particles is substantially lower than for feedback process described above. However, one needs a field with large extension (many characteristic lengths) in order obtain really big number of particles. The characteristic length of the feedback process may be somewhat larger, but only one such length is sufficient to produce the exponential increase of intensity of generated particles with time. So, in a limited volume this process can be dominant.

5. Acknowledgements

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