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Effects of thunderstorms electric field on the energy of cosmic ray electron

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Abstract. Studies on energy changes of cosmic ray electron in thunderstorms electric field are very important to understand the acceleration mechanism of secondary charged particles caused by electric field. In this paper, Monte Carlo simulations were performed with CORSIKA to study the energy of cosmic ray electron in two typical electric fields. One is upper than the threshold field strength resulting in a runaway breakdown process (i.e. the order of 1 kV/cm), the other is lower than that (i.e. the order of 0.1 kV/cm). The energy spectra of electrons and positrons were obtained in different fields at different altitudes, especially above YBJ (4300 m a.s.l., Tibet, China). The decrease of the ground cosmic ray in intensity during thunderstorms observed in ARGO-YBJ was discussed by using the simulation results.
Keywords: thunderstorms electric field, Monte Carlo simulations, electron energy spectrum, ARGO-YBJ

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1. Introduction

The atmospheric electric field can change the intensity of the extensive air shower (EAS) by accelerating or decelerating the charged particles. Especially during thunderstorms, the electric field with strength of the order up to 1 kV/cm may appear [1]. In 1925, Wilson [2] suggested that the strong electric field in the thunderstorms can cause observable effects on electron which has very tiny mass in the secondary cosmic ray. When the electron gains more energy from the electric field than it loses in various interactions with air, the energy of the electron will increase and lead to the occurrence of "runaway" electron. However, the conventional critical electric field strength to start this process is quite high ($\sim$10 kV/cm) and was never measured in thunderclouds [3]. Gurevich et al. [4] proposed a new breakdown mechanism based on a relativistic runaway electron avalanche (RREA) in 1992. Marshall et al.[5] and Dwyer [6] pointed out that this threshold field is of the order $\sim$1 kV/cm, about an order of magnitude lower than that needed for a conventional breakdown. The knocked-out electrons from the collisions of shower particles with air molecules or atoms are accelerated in the thunderstorms electric field. Under optimal conditions [7], they can gain enough energy, then the free electrons may become runaway and ionize further molecules, which results in avalanche process. The RREA process is believed to be the reasonable explanation of the initiation of lightning.

For years, scientists have carried out lots of ground-based experiments to detect the thunderstorm ground enhancements (TGEs) [8] and masses of satellite-borne experiments to investigate the terrestrial gamma flashes (TGFs) [9, 10], trying to find the high-energy electrons accelerated by the thunderstorms electric field or the high-energy rays radiated by bremsstrahlung.

Buitink et al.[7] found that the particle count rates increased in the field of 1 kV/cm by simulating the primary proton with energy higher than 10^{16} eV. They also obtained the energy spectra of electrons and positrons at different altitudes. Vanyan et al.[9] discussed the energy spectra of the electrons and photons in the uniform electric fields 1.7-2.0 kV/cm by simulating the RREA process. Chilingarian et al.[11] introduced two component models of the TGE origin by recovering the energy spectra of electrons and gamma rays from the thunderclouds, the RREA process and the modification of energy spectra (MOS) process. Recently, an analytical approach for calculating energy spectra of relativistic runaway electron avalanches in air has been proposed by Cramer et al.[12]. In their work, the energy spectra of the runaway electron population and the dependence of electron avalanche development on properties were discussed in detail. They found that the diffusion in energy space helped maintain an exponential energy spectrum for electric field that approaches the runaway electron threshold field.

Several detection researches on correlations between the intensity of the ground cosmic ray and the thunderstorms electric field were carried out at YBJ (4300 m a.s.l., Tibet, China) [13, 14]. They found that the particle count rates were not always increase in the field, in some cases it would decline. In this work, Monte Carlo simulations were performed with CORSIKA to study the effects of thunderstorms electric field on the energy of electrons and positrons in secondary particles at altitudes from 6400 to 4400 m.

2. Simulation setup

CORSIKA is a detailed Monte Carlo program to study the evolution and properties of extensive air showers in the atmosphere [15]. In this work, we simulated the energy spectra of the electrons in different fields by using CORSIKA 7.3700. The primary particle is a vertical 770 GeV proton. QGSJETII-04 was used for the high-energy hadronic interactions while GHEISHA for the low energy ones. Since electrons and positrons predominate in the secondary charged particles of the cosmic rays, and the apparent acceleration (or deceleration) of electric field on electrons (or positrons) is more obvious, the effects of electric field on electrons (or positrons) were properly taken into account in this work.

It has been found that the strength of the thunderstorms electric field can be high up to 1 kV/cm or even higher at YBJ. In our simulations, the electric field distributes from 6400 to 4400 m. It can be calculated the threshold field of the RREA process at 4400 m is higher than 1.6 kV/cm by using the formula proposed by Symbalisty et al. [16].

3. Simulation results

In order to get clues in the mechanism of electron acceleration in the thunderclouds, we chose two typical electric fields to discuss the accelerating mechanism by analyzing the longitudinal development and energy distribution of secondary charged particles. One is above the critical field of the RREA process (i.e. ± 1.7 kV/cm) and the other is the field below this threshold (i.e. ± 0.4 kV/cm). In view of the acceleration of the field, we set the energy cutoff below which electrons and positrons are discarded at 0.1 MeV in the simulation.

3.1 The longitudinal development of secondary particles

In our work, we took for granted the positive field was downward. In the positive field, the positrons (or electrons) are accelerated (or decelerated) downward, and dependent on the strength of the field, the fluxes of electrons and positrons reaching earth surface may exhibit significant amplification.

3.1.1 The longitudinal development of particles in electric field strength of 1.7 kV/cm

Figs.1-2 show the simulation results in electric field strength of 1.7 kV/cm, which is above the threshold field of the RREA process. The number of electrons (or positrons) is plotted as a function of atmospheric depth. The blue and red lines represent the development of electrons and positrons, respectively. The dashed lines correspond to the absence of an electric field and the solid lines correspond to the presence of a field. As shown in Fig.1, the number of positrons exceeds the number of electrons in the positive field (accelerating the positrons), causing a positive charge excess. The sum of electrons and positrons increases obviously. In Fig.2, we can apparently see an explosive increase in the number of electrons when the negative field is switched on. High up in the atmosphere, the number of electrons increases exponentially, and reaching a maximum at an atmospheric depth $\sim$560 g/cm^2. The energy cutoff at 0.1 MeV in our simulations may be of influence to the location of the maximum. These results are consistent with the theory of relativistic runaway electron avalanche (RREA).

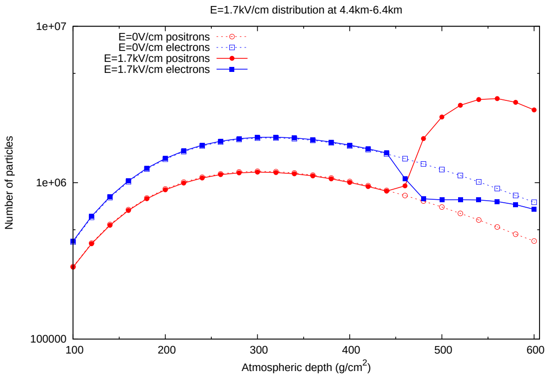

Fig. 1: Number of electrons and positrons as a function of atmospheric depth in an electric field of 1.7 kV/cm. (electric field area: 457-599 g/cm^2)

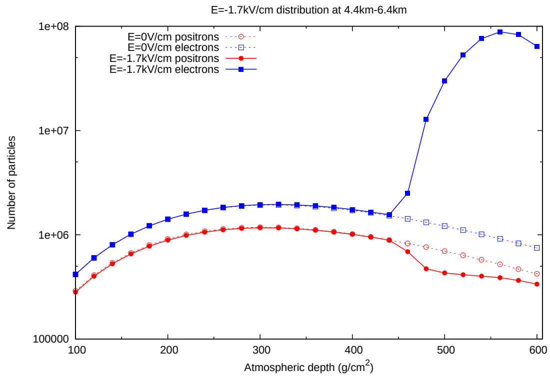

Fig. 2: Number of electrons and positrons as a function of atmospheric depth in an electric field of -1.7 kV/cm. (electric field area: 457-599 g/cm^2)

3.1.2 The longitudinal development of particles in electric field strength of 0.4 kV/cm

In Fig.3, the total number of electrons and positrons is plotted as a function of atmospheric depth in electric field strength of 0.4 kV/cm, which is far below the threshold field of the RREA process. The black dashed line is the evolution of electrons and positrons in absence of an electric field. The red and blue lines represent that in 0.4 kV/cm and -0.4 kV/cm, respectively. As we can see from Fig.3, the total population of electrons and positrons increases in negative electric field. While in the positive field, a certain degree decline occurs. Our simulations have the similar phenomenon with the experimental observations of ARGO-YBJ.

3.2 The energy spectra of electrons and positrons

It is well known that the slowing-down force of an electron in the air varies with its energy [17]. As low energetic electrons propagate through air, they lose their energies predominately from ionization losses. The drag force decreases with an increase of the energy. Electrons with initial kinetic energies larger than the threshold value, ε_{th} (~1 MeV, suggested by Gurevich [18]), may run away. Conversely, high energetic electrons lose energies mostly due to radiative losses such as bremsstrahlung. While the energy exceeds the maximum value ε_{max} (described by Buitink et al. [7]), the energy radiation losses dominate. Namely, electrons with initial kinetic energy ranging from ε_{th} to ε_{max}, may be accelerated in applied field. Beyond this energy value, electrons lose energy rapidly.

In order to understand the acceleration mechanism of secondary charged particles caused by electric field inside the thunderclouds, Monte Carlo simulations were performed with CORSIKA to study the energy spectra of cosmic ray particles in two typical electric fields, as described in the following.

3.2.1 The energy spectra of electrons and positrons in strong electric field

At first, we compared the energy distribution of electrons with positrons at the altitude of 4400 m in the absence of a field. As shown in Fig.4, in low energy range (~1-7 MeV), the ratio of electrons is larger than the ratio of positrons of the same energies. But the situation is reversed in higher energy range. That is to say that the ratio of positrons with energies above 7 MeV becomes more dominant. Based on the analysis above, it is easy to understand why the electric field alters the intensity of electrons more significantly than the intensity of the positrons.

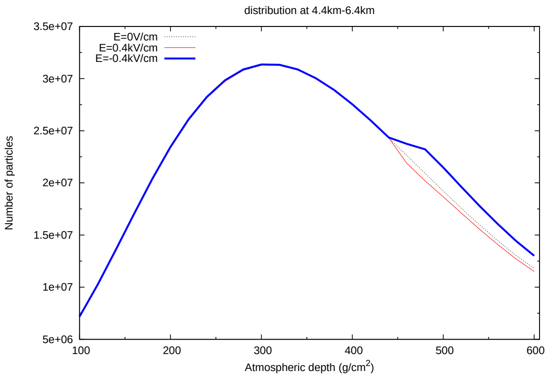

Fig. 3: Total number of electrons and positrons as a function of atmospheric depth in electric field strength of 0.4 kV/cm. (electric field area: 457-599 g/cm^2)

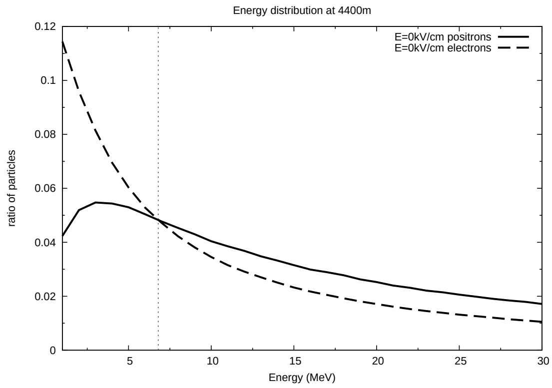

Fig. 4: The ratio distribution of electrons and positrons in energy range 1-30 MeV as a function of energy in absence of a field at the altitude of 4400 m

Fig.5 shows the energy distribution of electrons and positrons at the altitude of 4400 m in the electric field of -1.7 kV/cm. The same shower in absence of a field is plotted for reference. The two vertical lines represent special energies. The solid line is the maximum energy ε_{max}, the main effect of the particle acceleration is expected to occur below this energy, and no significant change is expected above this energy. We can see in Fig.5 that ε_{max} ~60 MeV at the altitude of 4400 m in -1.7 kV/cm. The dashed line represents the critical energy ε_c ~25MeV. When the energy is below ε_c, the particle multiplication comes from RREA process. In the range 1-25 MeV, the energy spectrum can be fitted by exponential function. While the energy is above ε_c, the particle experiences a normal accelerating process. At 25-60 MeV, the spectrum becomes power law. It means that there are two modes of particle generation. Seen from Fig.5, the RREA mode with maximal energy of electrons is ~25 MeV and the normal mode accelerates electrons up to ~60 MeV. The normal accelerating mode regime is fast fading after 60 MeV. As for positrons, the number of the same energy declines due to the deceleration of the negative field.

Fig.6 shows energy distribution of electrons in different fields at the altitude of 4400 m. The spectrum shapes of the electron in -1.7 kV/cm and -1.8 kV/cm are similar, but the flux and the maximum energy ε_{max} increase with the increasing field. It is in agreement with previous results [7]. We also notice that the spectrum shape in -1.5 kV/cm is different from the others. Because the field strength of 1.5 kV/cm is smaller than the threshold electric field, the particles in this field do not undergo the RREA process.

Fig.7 indicates the variation of the energy distribution of electrons at different altitudes. The electric field is switched on from the altitude of 6400 m. From the figure, we can see the flux increases with the increasing electric field length and the maximum energy ε_{max} becomes greater as well. The acceleration effects of the field length on particles are quite obvious.

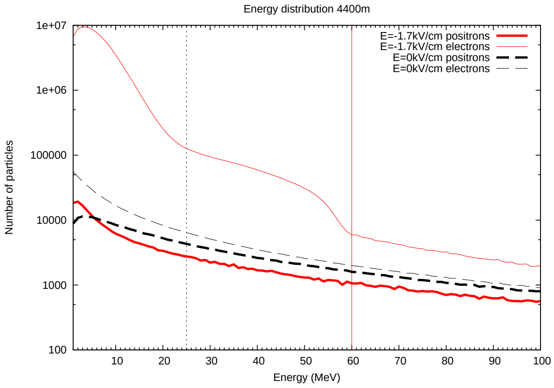

Fig. 5: Energy distribution of electrons and positrons in electric field of -1.7 kV/cm and the same in absence of a field at the altitude of 4400 m

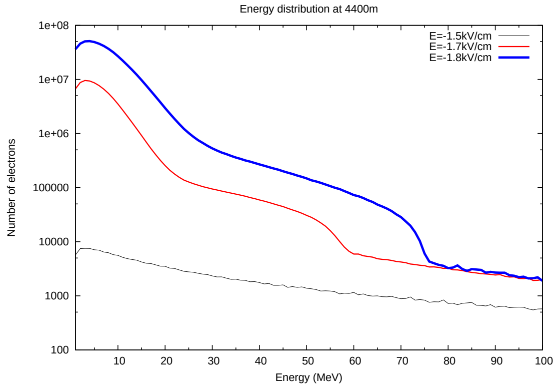

Fig. 6: Electron energy spectra at 4400 m altitude in different fields

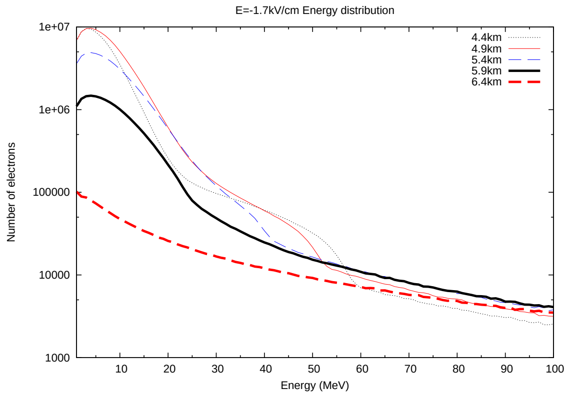

Fig. 7: Electron energy spectra at different altitudes in an electric field of -1.7 kV/cm

3.2.2 The energy spectra of electrons and positrons in an electric field of 0.4 kV/cm

As shown in Fig.8, the positrons are accelerated and the electrons are decelerated in the positive field. The red bold line corresponds to the change number of the positrons, and the dashed blue line to the change of the electrons and the continuous thin line to the change of total particles. We can see in Fig.8 that the increased number of positrons is apparently smaller than the decreased number of electrons of the same energies especially when the energy is below 20 MeV. There are two main factors may be taking into consideration. One is that the electric field has more obvious effects on the electrons which have smaller energy than the positrons. The other is that the number of positrons is less than the number of electrons due to Compton scattering effect. As a result, the change of the total number of positrons and electrons is negative in the energy range 1-20 MeV. While the energy is above 20 MeV, the effect of the electric field on electrons (or positrons) is very small. That is, the total number will decline in positive field of 0.4 kV/cm. The simulation results support the experimental observations of ARGO-YBJ.

Fig.9 shows the variation of the energy distribution of positrons in an electric field of 0.4 kV/cm at different altitudes. The electric field is switched on from the altitude of 6400 m. The flux of the positrons does not vary obviously; it decreases with the increasing electric field length. This result seems to be in contradiction to the result in strong field which is upper than the threshold field of the RREA process. It is reasonable because the energy gains from the small field are too weak to compensate the energy losses due to ionization in air with the decreasing altitude. However, when the applied field is strong enough, as shown in Fig.7, the energy gains become bigger and bigger with the increasing electric field length, leading to the enhancement of the particle flux.

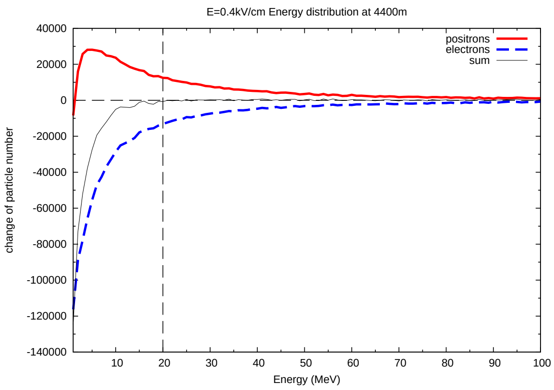

Fig. 8: The change of particle number as a function of energy in an electric field of 0.4 kV/cm at the altitude of 4400m

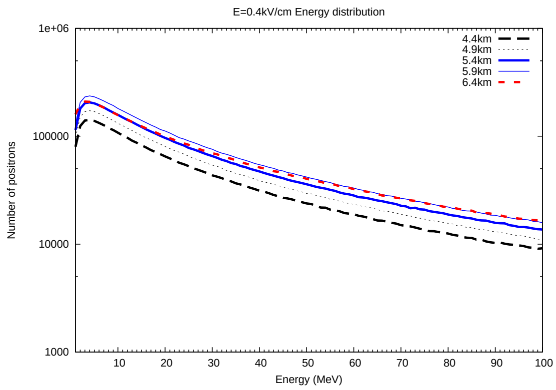

Fig. 9: Positron energy spectra at different altitudes in an electric field of 0.4 kV/cm

4. Conclusion

In this paper, Monte Carlo simulations were performed with CORSIKA to study the effects of thunderstorms electric field on electrons and positrons in secondary particles. We chose two typical electric fields to analyze the accelerating mechanism of secondary charged particles at altitudes from 6400 to 4400 m. One is above the critical field of the RREA process (±1.7 kV/cm) and the other is the field below this threshold (±0.4 kV/cm).

The intensity of electrons increases exponentially in an electric field of -1.7 kV/cm, which is consistent with the theory of relativistic runaway electron avalanche (RREA). Through analyzing the energy distribution of the electrons, we can see there are two modes of the acceleration in strong field. The RREA mode with maximal energy of electrons is ∼25 MeV and the normal mode accelerates electrons up to ∼60 MeV. The normal accelerating mode regime is fast fading after 60 MeV. We also discussed energy distribution of electrons in different negative fields at the altitude of 4400 m and the same in negative field of 1.7 kV/cm at different altitudes.

In a positive electric field strength of 0.4 kV/cm, the total number of electrons and positrons declines to some extent. Seen from the energy distribution, the total number of the electrons and positrons will decline in energy range of 20 MeV. Here may be two main reasons for this. One is that the electric field has more obvious effects on the electrons which have smaller energy than the positrons, the other is that the number of positrons is less than the number of electrons due to Compton scattering effect. These simulation results support the experimental observations of ARGO-YBJ.

In this work, we just simulated the case of uniform electric field and the primary proton of 770 GeV. Combined with the ambient electric field within thunderclouds, more cases (such as the different primary particle types, energies, incidence directions etc.) will be taken into account in further study.

Acknowledgments

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