

Simulation study on the relativistic runaway electron avalanche in thundercloud with CORSIKA*

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Abstract

Terrestrial Gamma-ray flashes (TGFs) originating from the Earth's atmosphere, accompanied by thunderstorms and lightning activity, are one of the hot spots in the interdisciplinary of cosmic ray and atmospheric physics. Over the years, satellite experiments have detected thousands of upward TGFs during thunderstorms, while ground-based experiments have observed some downward TGFs. Nowadays, it is widely believed that TGFs accompanying lightning leaders observed by satellite-based and ground-based experiments involve relativistic runaway electron avalanche (RREA) production. Due to triggering the relativistic runaway electron avalanche (RREA) process needing a very large electric field strength and region, it is difficult to study the RREA process through ground-based experiments. In this paper, CORSIKA 7.7410 software package, combined with a vertically uniform electric field model, is adopted to simulate the intensity and energy distribution of RREA electrons in thundercloud with different electric field strengths induced by seed electrons and the secondary electrons in extensive air shower (EAS) from

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vertical protons with different primary energies. The results show that the number of RREA electrons increases exponentially with the thickness of the thunderclouds increasing, and also increases exponentially with the electric field strength rising. After passing through the atmosphere with an electric field of -3000 V/cm and a thickness of 800 m, the number of secondary electrons in RREA process increases by approximately 3×10^4 times. The characteristic length of avalanche (λ) decreases as the electric field strength increases. When the electric field is -1600 V/cm and -3000 V/cm, the λ is approximately ~ 282 m and ~ 69 m, respectively. The energy spectrum of RREA electrons gradually softens with the increase of layer thickness and strength of electric field, and their average energy increases with the increase of electric field strength, when the thundercloud thickness exceeds 400 m, the mean energy of RREA electrons gradually stabilizes. When secondary particles pass through a thundercloud with an electric field strength of -3000 V/cm and a thickness of 800 m, the mean energy of RREA electrons is approximately 11.7 MeV. Through the Monte Carlo simulations, the RREA process, which is difficult to observe directly in the atmosphere, is successfully simulated. The simulation results provide important information for studying the characteristics of TGF source regions, offer clues for detecting downward TGF in ground-based experiments, and contribute to the research on the triggering mechanism of lightning in the atmosphere. In addition, our simulation results are expected to elucidate the relationship between TGF and lightning activity, promoting interdisciplinary research in the fields of atmospheric physics and cosmic ray physics.

Keywords: cosmic rays; relativistic runaway electron avalanche; thunderstorm electric field; Monte Carlo simulations

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1. Introduction

When the primary cosmic ray enters the atmosphere, it interacts with the atomic nuclei in the air. Through hadronic or electromagnetic interaction, it generates tens of thousands of secondary electrons, photons, muons, etc. which is called extensive air shower (EAS)^[1]. What will happen when these cosmic ray secondary particles pass through a thundercloud with a of kilometers (the atmospheric electric field in the cloud can be as high as 1000 V/cm, and some even exceed 2000 V/cm^[2-4])? As early as 1924, Wilson^[5] pointed out that the electric field of thundercloud accelerate electrons in the atmosphere (which was not related to cosmic rays at that time), and first proposed the concept of "runaway electrons". In 1992, Gurevich et al.^[6] proposed the theory of "runaway

breakdown" after considering electron-electron scattering (Moller scattering), which is now called "relativistic runaway electron avalanche (RREA)". They believe that electrons in the atmosphere (mainly from cosmic rays with high energy) are accelerated in the thunderstorm electric field to gain energy. When the energy gained exceeds the energy lost by ionization and bremsstrahlung, it will interact with atomic nuclei in the air to generate new electrons, triggering an avalanche process and causing the number of electrons to increase exponentially. This phenomenon of energetic particles produced by the acceleration of cosmic ray secondary electrons by thunderstorm electric field has become one of the research hot spots in the interdisciplinary of cosmic ray physics and atmospheric physics.

Since the RREA mechanism was proposed, scientists have tried to detect the high-energy particle radiation associated with thunderstorms and lightning activity through satellite experiments and ground-based experiments. In 1994, the terrestrial gamma-ray flash (TGF) from the Earth's atmosphere was first observed by the CGRO satellite^[7]. The discovery of TGF has attracted the interest of many researchers. In 1996, Inan et al. Found^[8] that TGF events may be related to lightning activity during thunderstorms. Up to now, satellite experiments such as BATSE^[9], Fermi^[10] and AGILE^[11] have detected thousands of TGFs events. China's "Wise Eye" satellite HXMT^[12] and "Huairou 1" polar satellite GECAM^[13] have also carried out a series of observational studies on TGF phenomena and obtained abundant observational data. Compared with the upward TGF observed by satellite experiments, the downward TGF events observed by ground experiments are not many due to the complex high-density atmospheric environment in the lower layer. In 2004, Dwyer et al.^[14] reported the first downward TGF event accompanied by an artificially triggered lightning leader. Since then, Hare et al.^[15], Enoto et al.^[16], Abbasi et al.^[17], Wada et al.^[18], and Belz et al.^[19] have successively observed downward TGF events based on ground-based experiments and believe that these observed phenomena are closely related to the occurrence process of thunderstorms and lightning.

At present, most of the theoretical discussions about TGF are based on the RREA mechanism proposed by Gurevich et al.^[6,20]. Dwyer^[21] and Symbalisky et al.^[22] studied the atmospheric electric field threshold E_{th} of RREA process through numerical calculation and simulation, and found that E_{th} is related to altitude, which can be expressed as $E_{th} = E_0 \exp(-Z/8.4)$, where $Z(\text{km})$ is altitude, $E_0 = 2800 \text{ V/cm}$ is the electric field threshold of triggering RREA mechanism at sea level. When the altitude is 4410 m, $E_{th} \approx 1660 \text{ V/cm}$. It can be seen that a strong electric field is needed to trigger the RREA process. In 2003, Dwyer^[21] used the Monte Carlo method to consider the ionization, excitation and Moller scattering between electrons and atmospheric molecules, and studied the avalanche length λ of the RREA mechanism. It was found that λ was related to the electric field strength and altitude, and could be approximately expressed as $\lambda = 7300 \text{ kV}/(E - 276 \text{ kV/m} \times n)$, where n was the density of air relative to that at sea level. When the altitude is 4410 m and the electric field strength is 2000 V/cm, the avalanche length constant of RREA mechanism is about 200 m, which shows that a large region is needed to trigger RREA process. In 2014, Skeltved et al.^[23] simulated the avalanche length $\lambda = 7400 \text{ kV}/(E - 298 \text{ kV/m})$ and $\lambda = 9770 \text{ kV}/(E - 285 \text{ kV/m})$, and the average energies of RREA electrons were 7.4 MeV and 9.7 MeV, respectively, under the electric field of 300 — 2500 kV/m through the "Low Background Experiment" (LBE) and the "Low- and High-Energy Parameterization" (LHEP) in the GEANT4 software package. It can be seen that under the LBE model, the results are relatively consistent with those obtained by Dwyer^[21], while under the LHEP model, there is a significant discrepancy.

In 2018, Li Xiaoqiang et al.^[24] used the Monte Carlo method to simulate the RREA process in a cylinder model with uniform atmospheric density, obtained the formula of the avalanche distance constant, and studied the energy of RREA electrons. Gurevich et al.^[6] also proposed the theory of lightning triggered by cosmic rays. They believed that when the secondary electrons of cosmic rays pass through thunderclouds, the RREA process will produce a large number of charged particles, which may trigger lightning. Therefore, the study of RREA mechanism is not only helpful to understand the phenomenon of high-energy radiation TGF in the atmosphere, but also expected to reveal the mystery of lightning triggering mechanism.

The process of trigger RREA requires a strong electric field and a large region, so it is difficult to directly observe and study it by experimental means. The use of Monte Carlo simulation method is conducive to a detailed and comprehensive study of the development process of RREA. In this paper, the CORSIKA software package is used to simulate the RREA process of cosmic ray secondary electrons in thunderclouds by adding the atmospheric electric field model, and the variation characteristics of the number and energy spectrum of RREA electrons with the atmospheric electric field strength and the thickness of the electric field layer in thunderclouds are studied.

2. CORSIKA software package and simulation parameters

CORSIKA (Cosmic Ray Simulations for Cascade)^[25] is an international general software package for simulating the process of ESA, which can record the type, energy and position of secondary particles in detail. CORSIKA software package includes a variety of particle interaction processes, such as electron and positron annihilation, Bhabha scattering, bremsstrahlung, Moller scattering and multiple scattering, as well as Compton scattering, electron pair effect and photoelectric effect. In addition, CORSIKA software package provides 41 kinds of atmospheric models (American standard atmospheric model, Central European atmospheric model, Antarctic atmospheric model, etc.). The American standard atmospheric model^[25] is used in this paper. Its atmosphere is composed of N₂, O₂ and Ar, accounting for 78.1%, 21% and 0.9%, respectively. The atmospheric boundary is defined at the height where the mass cover disappears (~ 112.8 km). The variation of atmospheric density with altitude is described in five layers, which is close to the real atmospheric distribution.

In this paper, CORSIKA version 7.7410 is used, the high-energy (greater than 80 GeV) strong interaction model is QGSJETII-04, and the low-energy (less than 80 GeV) strong interaction model is GHEISHA. In order to study the runaway avalanche effect of electrons in thunderstorm electric field, the RREA process of seed electrons with energy of 1 MeV, 10 MeV and 100 MeV in thundercloud is simulated, and the number and energy characteristics of RREA electrons are analyzed. In order to study the RREA process induced by cosmic ray secondary electrons in thunderclouds, the EAS process of primary protons (energy of 100 GeV, 1 TeV and 10 TeV) entering the atmosphere at normal incidence (zenith angle of 0 °) and the shower process

of secondary electrons in thunderclouds in EAS are simulated. Considering the acceleration effect of the electric field, the cut-off energy of the simulated electromagnetic particles (positrons, negative electrons and photons) is the minimum energy that CORSIKA can track, that is, 50 keV.

In order to describe the influence of the electric field on the electrons in the secondary particles of cosmic rays, an atmospheric electric field model is added to the CORSIKA software package^[26]. A uniform atmospheric electric field perpendicular to the ground (with the direction of the downward accelerating positron as the positive electric field) is added to this simulation. In real thunderclouds, the charge structure is complex, and the intensity and polarity of the atmospheric electric field change dramatically with time. In this simulation, a single and uniform electric field model is selected. Although there is a certain deviation between the simulation results and the actual situation, the direct relationship between the thunderstorm electric field and the cosmic ray variation can be obtained. In this paper, the development of seed electrons and cosmic ray secondary electrons above the threshold of the escape avalanche electric field (-1600 , -1800 , -2000 , -2200 , -2400 , -2600 , -2800 and -3000 V/cm) is simulated, respectively. For comparison, the simulation is also carried out for the case of no electric field and less than the threshold of the escaping avalanche electric field.

3. Simulation result

In this work, the CORSIKA software package is used to simulate the relativistic runaway electron avalanche process induced by seed electrons and secondary electrons of the primary proton shower in the thunderstorm electric field, respectively, and to study the intensity and energy distribution of RREA electrons.

3.1 RREA electrons produced by seed electrons in thunderclouds

According to Wilson^[5]'s concept of "runaway electrons" and Gurevich^[6]'s physical mechanism of "RREA", the seed electrons entering the high electric field region (above the electric field threshold of RREA) will produce a large number of relativistic runaway electrons, which will lead to the exponential multiplication of the number of electrons. The Fig. 1 is a shower process of a seed electron (initial energy 100 MeV) entering a thundercloud simulated by CORSIKA, in which the atmospheric electric field is 0, -1500 , -1800 , -2000 , -2500 and -3000 V/cm, respectively, and the thickness of the electric field layer is 800 m (the altitude Z is 4710 — 5510 m). The simulation results show that different electric fields have a significant effect on the development of seed electrons. In the absence of external electric field, the seed electrons develop slowly, and the shower process stops at an altitude of 5200 m due to the ionization energy loss. When an electric field (less than the RREA field threshold) is applied, the number of secondary electrons increases due to the acceleration of the electric field. When the electric field in thundercloud is greater than the threshold of RREA, the seed electrons trigger the RREA

process, and the number of secondary electrons increases by avalanche multiplication. When the electric field is -3000 V/cm, the number of RREA electrons is as high as 1.5×10^4 after a seed electron passes through a thundercloud of 800 m.

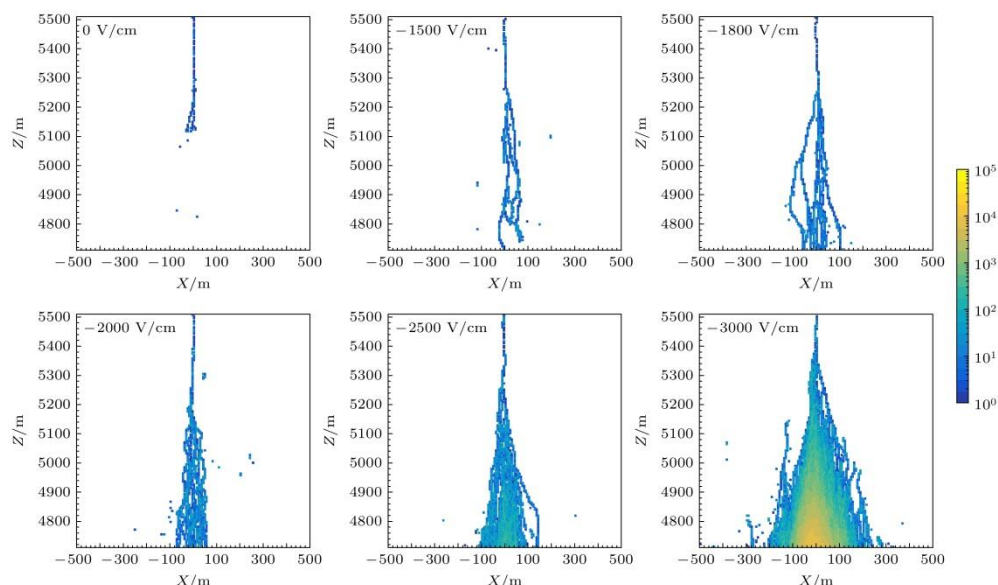


Figure 1. Cascade process of seed electrons (100 MeV) in different electric fields.

How about the energy distribution of RREA electrons in thunderclouds? Fig. 2 is the energy distribution of RREA electrons generated by seed electrons with primary energies of 1, 10 and 100 MeV passing through thunderclouds with an electric field of -3000 V/cm (the thickness of the electric field layer is 800 m). The Fig. 2 show that most of the RREA electrons are concentrated in the low energy region less than 20 MeV, and the number of RREA electrons decays exponentially with the increase of the secondary electron energy.

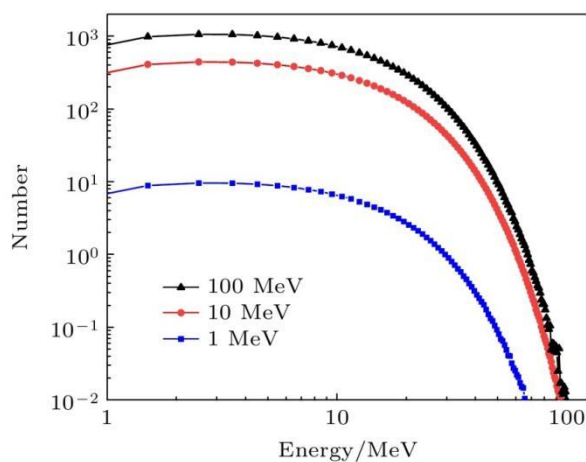


Figure 2. Energy distributions of RREA electrons induced by seed electron for different primary energies in -3000 V/cm.

The average energy of RREA electrons produced by seed electrons with different primary energies varies with the thickness of the electric field layer in the thundercloud (electric field of -3000 V/cm) as shown in Fig. 3(a). When the thickness of the electric field layer in the cloud is

small, the average energy of the secondary electrons is related to the primary energy of the seed electrons. When the seed electron energy is 1 MeV and 10 MeV, due to the influence of Coulomb scattering, the angle between the motion direction of most secondary electrons and the direction of the electric field increases, and the secondary electrons lose energy under the action of atmospheric ionization and cannot reach the detection surface. The surviving secondary electrons move almost along the direction of the electrical field and gain energy under the action of electric field acceleration, and their average energy varies. When the seed electron energy is 100 MeV, a large number of low-energy RREA electrons are produced, and their average energy decreases rapidly with the increase of the thickness of the electric field layer. With the continuous increase of the thickness of the electric field layer in the thundercloud, the proportion of RREA electrons in the secondary electrons increases gradually, and the difference between the seed electrons with different primary energies decreases gradually. When the thickness of the electric field layer in the thundercloud is larger than 400 m, the energy gained by the RREA electrons in the electric field is equivalent to the energy lost, and the average energy tends to be stable.

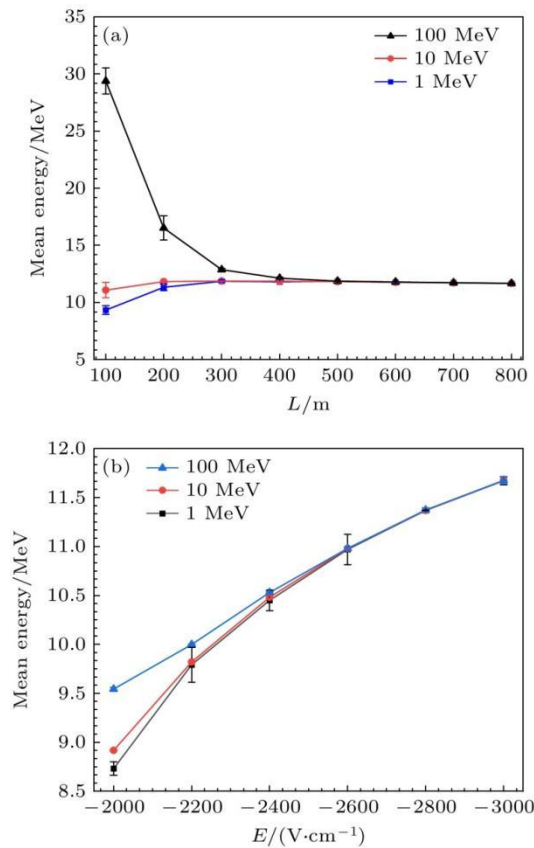


Figure 3. Mean energy of RREA electrons induced by seed electron as a function of the layer thickness (a) and strength (b) of the electric field.

The Fig. 3(b) gives the relationship between the average electron energy of the RREA and the electric field strength (the vertical scale of the electric field region within the cloud is 800 m). The Fig. 3 show that the average energy of RREA electrons increases with the increase of electric field intensity in thundercloud, and the difference between seed electrons with different initial

energy decreases gradually. For 1 MeV and 100 MeV seed electrons, the average energy difference of RREA electrons is 0.8 MeV when the electric field is -2000 V/cm, while the average energy difference of RREA electrons is only 0.004 MeV when the electric field is -3000 V/cm. According to the Fig. 3(a) and Fig. 3(b), the average energy of RREA electrons is about 11.7 MeV when the electric field is -3000 V/cm and the thickness of the electric field layer is 800 m.

3.2 The process of producing RREA in thundercloud by secondary electrons of primary proton shower

The primary cosmic rays from cosmic space enter the atmosphere and produce a large number of secondary electrons, which increase with the increase of the energy of the primary cosmic rays. These secondary electrons enter the strong electric field of thundercloud as seeds, which will trigger the RREA process and produce a large number of RREA electrons. The intensity and energy distribution characteristics of RREA electrons produced by secondary electrons of primary proton showers (with different primary energies) entering thunderclouds (at an altitude of 4710-5510 m) are simulated below.

3.2.1 Relationship between the number of RREA electrons and the vertical scale and electric field intensity of the electric field region in thunderclouds

Cosmic ray protons with different primary energies enter the thundercloud with an electric field intensity of -3000 V/cm through the EAS process, and the number of secondary electrons produced varies with the vertical scale L of the electric field region in the thundercloud as shown in the Fig. 4. The number of secondary electrons multiplies with the increase of the vertical scale of the electric field in the thundercloud. Protons with primary energies of 100 GeV, 1 TeV and 10 TeV shower in the atmosphere, and the number of secondary electrons is 6, 140 and 2.5×10^3 respectively when they reach 5510 m above sea level (before entering the thundercloud), and increases to 2.3×10^5 , 4.4×10^6 and 7.89×10^7 respectively when they reach 4710 m above sea level through 800 m thundercloud (electric field in the cloud -3000 V/cm). It can be seen that the number of secondary electrons in the RREA process increases exponentially, and the greater the primary energy, the more secondary electrons are generated through the EAS process before entering the thundercloud (that is, the more seed electrons), resulting in the more RREA electrons generated in the thundercloud. After passing through the 800 m thundercloud, the number of secondary electrons with different primary energies increases by $\sim 3 \times 10^4$ times. It can be seen that the newly generated RREA electrons account for the vast majority.

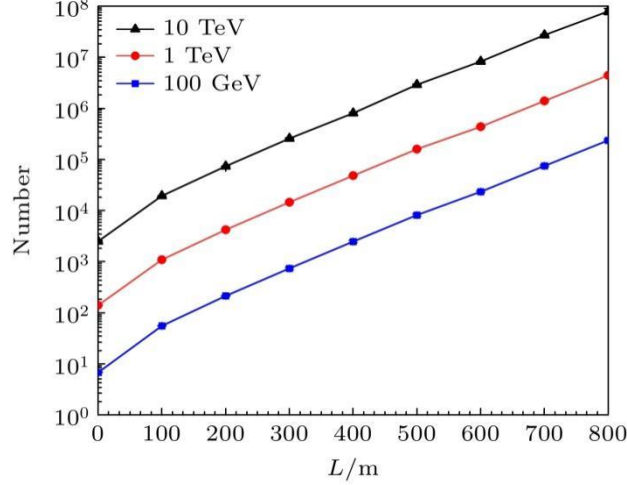


Figure 4. Number of secondary electrons induced by protons as a function of the thickness of the electric field layer for different primary energies.

Gurevich et al.^[6] predicted that the number of secondary electrons N_{re} in the RREA process is related to the length L of the escape avalanche region in the thundercloud, and satisfies the following relationship:

$$N_{re} = N_0 \exp(L/\lambda), \quad (1)$$

Where N_0 is the number of seed electrons and λ is the avalanche length. Transform (1) as follows:

$$\lambda = L/\ln(N_{re}/N_0). \quad (2)$$

According to the relationship between the number of RREA electrons in the Fig. 4 and thickness of the electric field layer, the avalanche length λ under different electric field intensities can be obtained by using the formula (2), see Fig. 5. It can be seen that the avalanche length λ decreases rapidly with the increase of electric field strength, and when the electric field is -1600 V/cm, $\lambda \approx 282$ m; When the electric field is -3000 V/cm, $\lambda \approx 69$ m. This means that after the same avalanche distance, the greater the electric field strength in the thundercloud, the more the number of RREA electrons will be. The relationship between the avalanche length λ and the electric field intensity E in Fig. 5 is fitted to obtain the following formula:

$$\lambda(E) = 12797 \text{ kV} / (E - 114.8 \text{ kV/m}). \quad (3)$$

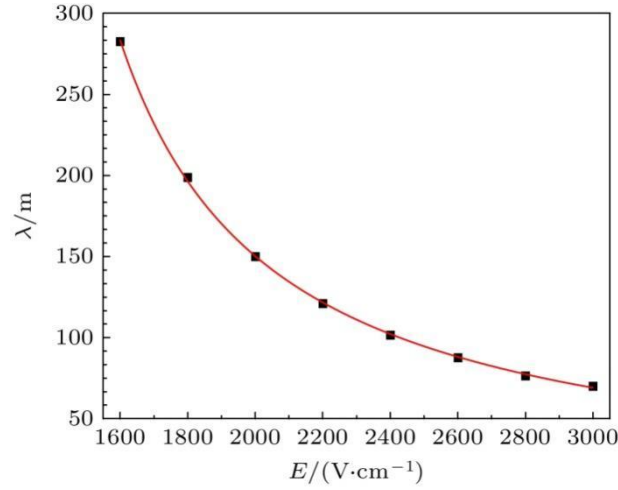


Figure 5. Avalanche length λ as a function of electric field strength.

According to the relationship between the field strength threshold E_{th} and the altitude^[21,22], the field strength threshold E_{th} is 1600 V/cm at an altitude of 4710 m, which indicates that the RREA process is triggered only when the electric field strength is greater than 1600 V/cm. In order to better study the development of RREA under different electric fields, the secondary electrons of the primary proton shower are simulated under the condition of a fixed electric field with a vertical scale of 800 m, and the relationship between the number of secondary electrons and the electric field intensity of thunderstorm is analyzed. The Fig. 6 shows the variation of the number of secondary electrons with the thunderstorm electric field after the cosmic ray protons with different primary energy pass through the thundercloud through the EAS process.

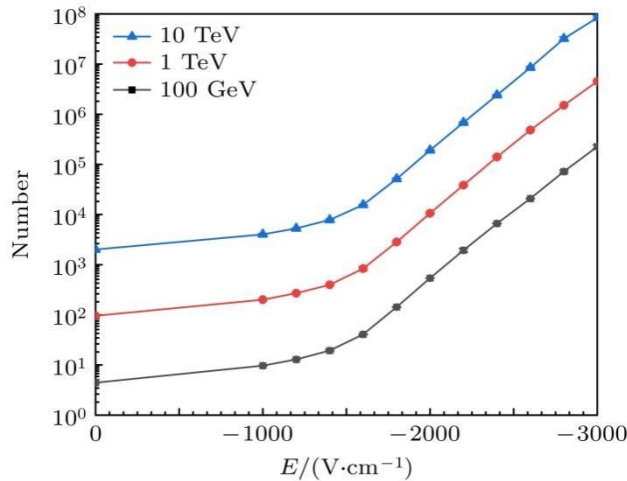


Figure 6. Number of secondary electrons induced by protons as a function of the electric field strength for different primary energies.

From the Fig. 6, it can be seen that when the electric field strength is lower than the threshold of the escape electric field, the number of secondary electrons increases slowly under the acceleration of the electric field. In an electric field of -1600 V/cm, the number of secondary electrons at 100 GeV, 1 TeV and 10 TeV is 40, 8.35×10^2 and 1.56×10^4 , respectively, which is

6.7, 6.0 and 6.2 times of that without electric field. When the applied electric field strength is greater than the threshold of the escape electric field, the number of secondary electrons increases exponentially. Under the electric field of -3000 V/cm, the numbers of secondary electrons are 2.3×10^5 , 4.4×10^6 and 7.89×10^7 , respectively, which are 3.3×10^4 , 3.1×10^4 and 3.1×10^4 times of those without electric field. The above results show that when the electric field strength exceeds the threshold of the escape electric field, the number of secondary electrons increases rapidly and further increases with the increase of the primary energy.

The variation of the $\ln(N_{re}/N_0)$ with the avalanche field multiple δ ($\delta = E/E_{th}$, $E_{th} = -1600$ V/cm) is shown in Fig. 7. When the applied electric field is greater than the threshold of the escaping avalanche electric field, there is a linear positive correlation between $\ln(N_{re}/N_0)$ and δ at different primary energies, and the proportional coefficient is 9.7 ± 0.1 , that is, $\ln(N_{re}/N_0) \approx 9.7\delta$, that is, the number of secondary electrons in the RREA process increases exponentially with the electric field intensity in the thundercloud.

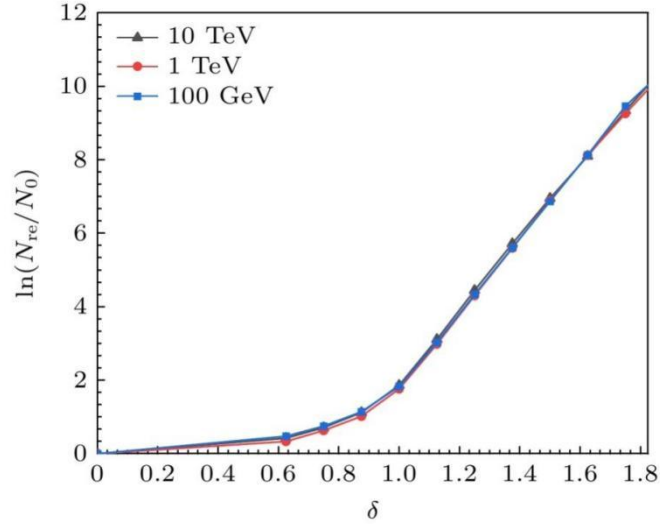


Figure 7. $\ln(N_{re}/N_0)$ as a function of different values of δ for different primary energies.

When the electric field strength in the thundercloud exceeds the threshold of the escape avalanche electric field, the RREA process will be triggered, accompanied by the generation of a large number of RREA electrons. The number of RREA electrons is closely related to the avalanche length and the electric field strength in the thundercloud, as well as the energy of the primary particles. It can be seen from the Fig. 4 and Fig. 6 that the number of RREA electrons is positively correlated with the energy of the primary particles, that is, the higher the primary energy, the more the number of RREA electrons. This phenomenon indicates that the primary energetic particles can significantly increase the number of secondary electrons by triggering the RREA process, thus providing a possibility and theoretical basis for the further participation of RREA electrons in the atmosphere in the lightning triggering process.

3.2.2 Relationship between RREA electron energy and electric field intensity, thickness of electric field layer in thundercloud

In order to study the characteristics of the energy distribution of secondary electrons, cosmic ray protons with an primary energy of 10 TeV pass through an EAS process and pass through a thundercloud with an electric field area of 800 m. The relationship between the energy distribution of secondary electrons and the electric field strength is shown in Fig. 8. With the increase of the electric field strength, the number of secondary electrons increases and their energy spectrum becomes softer. That is to say, with the increase of thunderstorm electric field intensity, the increase of electrons in the low-energy region is greater. Compared with no electric field, the secondary electrons with energy less than 70 MeV and more than 100 MeV increase by about 120% and 40% in the electric field of -1000 V/cm, and by 5.6×10^4 and 10^2 times in the electric field of -3000 V/cm, respectively. This is because when the low-energy electrons are accelerated in the electric field, the energy lost by bremsstrahlung is small, and they can continue to gain energy to produce secondary electrons, so that the RREA electrons are mainly concentrated in the low-energy region. The high-energy electrons mainly come from the secondary electrons produced in the EAS process. With the increase of the electric field strength, the number of high-energy electrons that survive increases, but the increase is much lower than that of low-energy electrons.

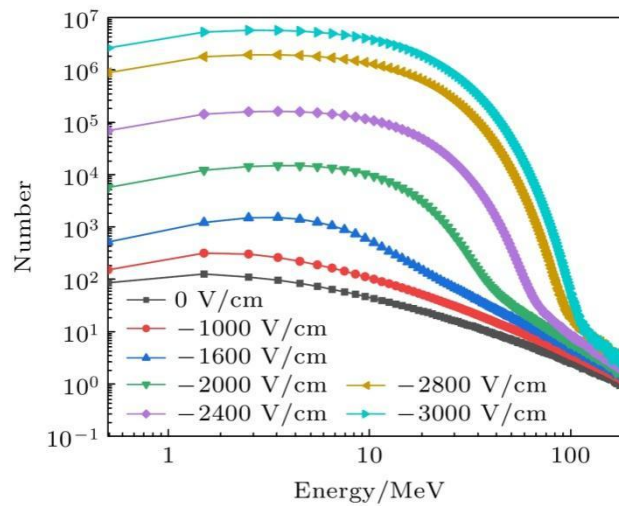


Figure 8. Energy distribution of secondary electrons induced by protons (10 TeV) with respect to electric field strength.

Cosmic ray protons with an primary energy of 10 TeV pass through the EAS process and enter the thundercloud with an electric field of -3000 V/cm. The relationship between the energy distribution of the generated RREA electrons and the thickness of the electric field layer in the thundercloud is shown in Fig. 9. With the increase of the thickness of the electric field layer, the number of secondary electrons increases and their energy spectrum becomes softer. When the

thickness of the electric field layer in the cloud reaches 500 m, the number of secondary electrons with energy less than 70 MeV increases by about 1.5×10^3 times, while the number of secondary electrons with energy greater than 100 MeV increases by only about 1.7 times, which indicates that the newly added secondary electrons are mainly concentrated in the low energy region. With the further increase of the thickness of the electric field layer, the energy spectrum of the secondary electrons gradually slows down and tends to be stable, indicating that the influence of the RREA process on the electron energy distribution gradually reaches saturation when the thickness of the electric field layer in the thundercloud reaches a certain value.

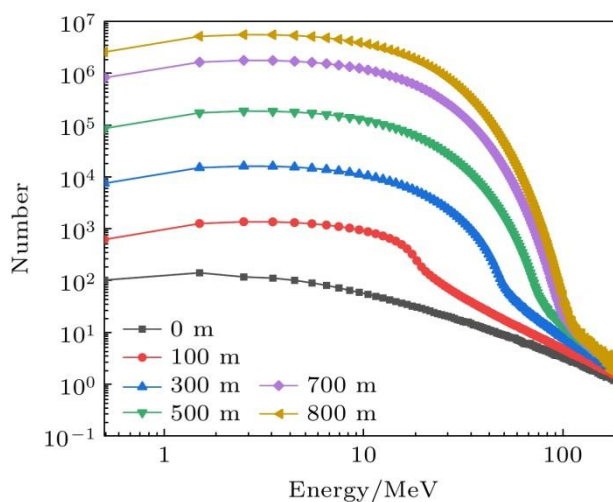


Figure 9. Energy distribution of secondary electrons induced by protons (10 TeV) with respect to thickness of the electric field layer.

The Fig. 10(a) shows the relationship between the average energy of secondary electrons produced by cosmic ray protons with different primary energies in the EAS process and the thickness of the electric field layer in the thundercloud (the electric field is -3000 V/cm). The simulation shows that the secondary electrons produced by cosmic ray protons with primary energies of 100 GeV, 1 TeV and 10 TeV before entering the thundercloud (at an altitude of 5510 m) have higher energies, with average energies of 62 MeV, 91 MeV and 121 MeV, respectively. After entering the thunderscloud, the secondary electrons in the cosmic ray proton shower trigger the RREA process and produce a large number of new low-energy electrons (RREA electrons), whose average energy decreases rapidly with the increase of the thickness of the electric field layer; As the thickness of the electric field layer continues to increase, the proportion of newly generated RREA electrons increases gradually. When the thickness of the electric field layer in the thunderstorm cloud exceeds 400 m, the secondary electrons are almost newly generated RREA electrons. The energy gained by these electrons in the electric field is equivalent to the energy lost, and their average energy gradually tends to be stable.

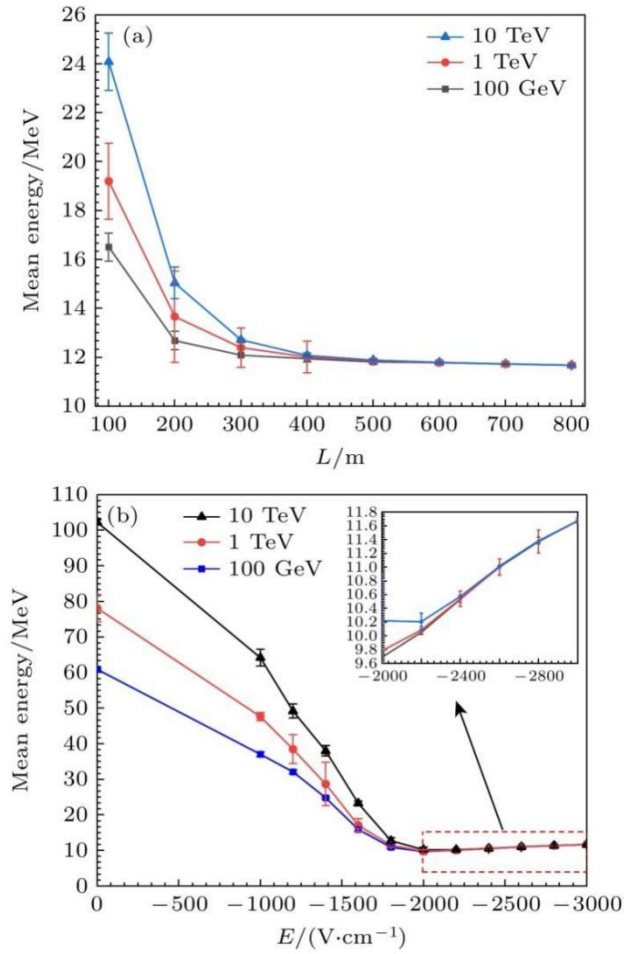


Figure 10. Mean energy of secondary electrons as a function of the layer thickness (a) and strength (b) of the electric field.

Fig. 10(b) is the relationship between the average energy of secondary electrons produced by cosmic ray protons with different primary energy in EAS and the thunderstorm electric field (the thickness of the electric field layer is 800 m). It can be seen that the larger the primary energy is, the higher the average energy of the secondary electrons is. When the electric field strength is lower than the field strength threshold, more low-energy secondary electrons in the shower gain energy and reach the detection threshold under the acceleration of the electric field, so that their average energy decreases rapidly with the increase of the electric field strength. When the electric field strength is greater than the threshold of the escape electric field, a large number of RREA electrons will be produced. The energy gained by these electrons from the electric field is greater than the energy lost, and their average energy increases slowly with the increase of the electric field strength, and the difference between different initial energies gradually decreases. When the electric field is $-3000 V/cm$ and the thickness of the electric field layer is 800 m, the average energy of RREA electrons is about 11.7 MeV, which is consistent with the average energy of RREA electrons obtained by the seed electron simulation.

Comparing the average electron energy of RREA with the results of Dwyer et al.^[27] and Babich et al.^[28] (7.3 MeV), the average electron energy of RREA in this study is larger. This

difference is mainly caused by two aspects: one is that the cutoff energy of secondary electrons in this paper is the minimum energy allowed by CORSIKA (50 keV), while the statistics of Babich et al.^[28] includes all electrons above 1 keV, which leads to the larger average energy obtained in this paper; Secondly, there are differences in the software packages and models used in different studies. In this paper, the CORSIKA software package is used to simulate the extensive air shower process, while Dwyer et al.^[27] uses the 3-D MC method, and Babich et al.^[28] uses the ELIZA MC code. In addition, Skeltved et al.^[23] used different models to obtain the average energy of secondary electrons of 7.4 MeV and 9.7 MeV, respectively, which further indicates that there may be some differences in the calculation results between different models. The atmospheric model and thunderstorm model involved in CORSIKA software package are more in line with the real situation, and the particle action process is more comprehensive, so the simulation results have greater practical value.

4. Conclusion

In this paper, the process of relativistic runaway electron avalanche induced by seed electrons and secondary electrons of primary protons in thunderstorm clouds is simulated by Monte Carlo method using CORSIKA 7.7410 software package, and the intensity and energy distribution of RREA electrons are studied. When the electric field strength is greater than the threshold of avalanche escape, the number of RREA electrons produced by seed electrons with primary energy of 1 MeV, 10 MeV and 100 MeV all shows avalanche multiplication phenomenon, and the average energy of RREA electrons increases with the increase of electric field strength. When the thickness of the electric field layer in thundercloud is large enough, the average energy of RREA electrons gradually tends to be stable. The simulation of the RREA process of the secondary electrons of the primary proton shower in the strong electric field of thunderstorm shows that the number of RREA electrons increases exponentially with the increase of the vertical scale and electric field strength of the electric field region at different primary energies. When the electric field is -3000 V/cm, the number of secondary electrons of a primary proton shower with an energy of 10 TeV can be as high as 7.89×10^7 after passing through a thunderstorm cloud of 800 m, which provides the possibility for high-energy cosmic rays to trigger lightning in the atmosphere. The secondary electrons in the RREA process are mainly concentrated in the low energy region, and their energy spectra become softer with the increase of the vertical scale of the electric field region and the electric field strength. Compared with no electric field, in the electric field of -3000 V/cm (the thickness of the electric field layer inside the cloud is 800 m), the secondary electrons with energy less than 70 MeV increase by 5.6×10^4 , while the secondary electrons with energy greater than 100 MeV increase by 100 times, that is to say, the secondary electrons of lower energy occupy the vast majority in the RREA process. In the electric field of 2000-3000 V/cm, the average energy of secondary electrons increases with the increase of the electric field. When the electric field is -3000 V/cm and the thickness of the electric field layer is

greater than 400 m, the energy gained by RREA electrons in the electric field is equivalent to the energy lost, and the average energy tends to be stable (~ 11.7 MeV).

In this paper, the Monte Carlo method is used to simulate the RREA process, which is difficult to observe directly and can be reproduced in the laboratory, and the development process of RREA is studied in detail. The results provide important information for further understanding the physical mechanism of TGF phenomenon in satellite and ground experiments, and are helpful for the study of lightning triggering mechanism.

References

- [1] Huang Z H, Zhou X X, Huang D H, Jia H Y, Chen S Z, Ma X H, Liu D, Axikegu, Zhao B, Chen L, Wang P H 2021 *Acta Phys. Sin.* **70** 199301
- [2] Liu D X, Qie X S, Wang Z C, Wu X K, Pan L X 2013 *Acta Phys. Sin.* **62** 219201
- [3] Marshall T C, Stolzenburg M, Maggio C R, Coleman L M 2005 *Geophys. Res. Lett.* **32** L03813
- [4] Stolzenburg M, Marshall T C, Rust W D, Bruning E, MacGorman D R, Hamlin T 2007 *Geophys. Res. Lett.* **34** L04804
- [5] Wilson C T R 1924 *Proc. Phys. Soc. London* **37** 32D
- [6] Gurevich A V, Milikh G M, Roussel-Dupre R 1992 *Phys. Lett. A* **165** 463
- [7] Lü F C, Zhang Y J, Lu G P 2023 *Sci. China-Earth Sci.* **53** 421
- [8] Inan U S, Reising S C, Fishman G J, Horack J M 1996 *Geophys. Res. Lett.* **23** 1017
- [9] Fishman G J, Bhat P N, Mallozzi R, Horack J M, Koshut T, Kouveliotou C, Pendleton G N, Meegan C A, Wilson R B, Paciesas W S, Goodman S, Christian H 1994 *Science* **264** 1313
- [10] Briggs M S, Fishman G J, Connaughton V, Bhat P N, Paciesas W S, Preece R D, Wilson-Hodge C, Chaplin V L, Kippen R M, Kienlin A V, Meegan C A, Bissaldi E, Dwyer J R, Smith D M, Holzworth R H, Grove J E, Chekhtman A 2010 *J. Geophys. Res.* **115** A07323
- [11] Marisaldi M, Fuschino F, Labanti C, Galli M, Longo F, Del Monte E, Barbiellini G, Tavani M, Giuliani A, Moretti E, et al. 2010 *J. Geophys. Res.* **115** A00E13
- [12] The Insight-HXMT team 2020 *Sci. China-Phys. Mech. Astron.* **63** 249502
- [13] Chen C, Xiao S, Xiong S L, Yu N, Wen X Y, Gong K, Li X Q, Li C Y, Hou D J, Yang X T, Zhao Z J, Zhu Y X, Zhang D L, An Z H, Zhao X Y, Xu Y P, Wang Y S 2021 *Exp. Astron.* **52** 45
- [14] Dwyer J R, Rassoul H K, Al-Dayeh M, Caraway L, Wright B, Chrest A, Uman M A, Rakov V A, Rambo K J, Jordan D M, Jerauld J, Smyth C 2004 *Geophys. Res.*

Lett. **31** L05119

- [15] Hare B M, Uman M A, Dwyer J R, Jordán D M, Blüggerstaff M L, Caicedo J A, Carvalho F L, Wilkes R A, Kotovsky D A, Gamera W R, Pilkey J T, Ngim T K, Moore R C, Rasoule H K, Cummer S A, Grove J E, Nag A, Betten D P, Bozarth A 2016 *J. Geophys. Res. Atmos.* **121** 6511
- [16] Enoto T, Wada Y, Furuta Y, Nakazawa K, Yuasa T, Okuda K, Makihima K, Sato M, Sato Y, Nakano T, Umemoto D, Tsuchiya H, GROWTH Collaboration 2017 *Nature* **551** 481
- [17] Abbasi R U, Abu-Zayyad T, Allen M, Barcikowski E, Belz J W, Bergman D R, Blake S A, Byrne M, Cady R, Cheon B G, et al. 2018 *J. Geophys. Res. Atmos.* **123** 6864
- [18] Wada Y, Enoto T, Nakazawa K, Furuta Y, Yuasa T, Nakamura Y, Morimoto T, Matsumoto T, Makishima K, Tsuchiya H 2019 *Phys. Rev. Lett.* **123** 061103
- [19] Balz J W, Krehbiel P R, Remington J, Stanley M A, Abbasi R U, LeVon R, Rison W, Rodeheffer D, Abu-Zayyad T, Allen M, et al. 2020 *J. Geophys. Res. Atmos.* **125** e2019JD031940
- [20] Qie X S, Wang J F 2010 *Adv. Earth Sci.* **25** 893
- [21] Dwyer J R 2003 *Geophys. Res. Lett.* **30** 2055
- [22] Symbalisty E M D, Roussel-Dupre R A, Yukhimuk V A 1998 *IEEE Trans. Plasma Sci.* **26** 1575
- [23] Skeltved A B, Ostgaard N, Carlson B, Gjesteland T, Celestin S 2014 *J. Geophys. Res.* **119** 9174
- [24] Li X Q, Zhou H Z, Jiang R B, Li P, Song L J, Li Y N, Li W, Zheng Y 2018 *Nucl. Electron. Detect. Technol.* **38** 0360
- [25] Heck D, Knapp J, Capdevielle J N, Schatz G, Thouw T 1998 FZKA: Forschungszentrum Karlsruhe GmbH, Karlsruhe, 6019, <https://www.ikp.kit.edu/corsika/70.php>
- [26] Zhou X X, Wang X J, Huang D H, Jia H Y 2016 *Chin. J. Space Sci.* **36** 49
- [27] Dwyer J R, Smith D M, Cummer S A 2012 *Space Sci. Rev.* **173** 133
- [28] Babich L P, Donskoy E N, Il'KaeV R I, Kutsyk I M, Roussel-Dupre R A 2004 *Plasma Phys. Rep.* **30** 616