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# Effect of near-earth thunderstorms electric field on the intensity of ground cosmic ray positrons/electrons in Tibet

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ABSTRACT

Monte Carlo simulations are performed to study the correlation between the ground cosmic ray intensity and near-earth thunderstorms electric field at YBJ (located at YangBaJing, Tibet, China, 4300 m a. s. l.). The variations of the secondary cosmic ray intensity are found to be highly dependent on the strength and polarity of the electric field. In negative fields and in positive fields greater than 600 V/cm, the total number of ground comic ray positrons and electrons increases with increasing electric field strength. And these values increase more obviously when involving a shower with lower primary energy or a higher zenith angle. While in positive fields ranging from 0 to 600 V/cm, the total number of ground comic ray positrons and electrons declines and the amplitude is up to 3.1% for vertical showers. A decrease of intensity occurs in inclined showers within the range of 0–500 V/cm, which is accompanied by smaller amplitudes. In this paper, the intensity changes are analyzed, especially concerning those decreasing phenomena in positive electric fields. Our simulation results could be helpful in understanding the decreases observed in some ground-based experiments (such as the Carpet air shower array and ARGO-YBJ), and also be useful in understanding the acceleration mechanisms of secondary charged particles caused by an atmospheric electric field.



## 1. Introduction

The effect of thunderstorms electric field on the development of cosmic ray air showers, especially on the intensity of secondary cosmic rays, is one of the hottest topics in high-energy atmospheric physics. During thunderstorms, the maximum strength of electric fields has been found in the range of 850–1300 V/cm [1], or even up to 2000 V/cm [2,3]. In such strong fields, by accelerating or decelerating the charged particles in extensive air showers, the intensity of secondary cosmic rays could be influenced. It was first suggested by Wilson [4] in 1924 that the strong electric field during thunderstorms might result in an observable effect on a secondary electron, which has tiny mass. In 1992, Gurevich et al. [5] suggested an avalanche-type increase of the number of runaway electrons could lead to a new type of electric breakdown of gases in the atmosphere. They developed the theory of runaway breakdown (RB), now mostly referred to as relativistic runaway electron avalanche (RREA) [6]. Marshall et al. [3,7], Dwyer [8] and Symbalisty et al. [9] studied the strength of threshold field necessary for an avalanche to occur, which is strongly dependent on the altitude.

For decades, many scientists have carried out a wide range of ground-based experiments to detect the thunderstorm ground enhancement (TGE), a new high-energy phenomenon originating in the terrestrial atmosphere, trying to find high-energy electrons accelerated by thunderstorms electric field or high-energy photons radiated by bremsstrahlung. The intensity enhancements of ground cosmic rays have been detected by high altitude experiments, such as the Carpet air shower array [10,11], EAS-TOP [12], ASEC [13–17] and AS$\gamma$ [18]. Their results indicated that the increases were associated with the electric field and the RREA process could be responsible for huge TGEs. Tsuchiya et al. [18–20] and Torii et al. [21–22] provided clear evidence that strong electric fields can accelerate electrons beyond a few tens of MeV.

It is well known that the strong electric discharges associated with thunderstorms can produce terrestrial gamma-ray flash (TGF). For years, thousands of TGFs have been detected by satellite-based experiments, such as AGILE [23] and Fermi-GBM [24]. The lightning initiation and correlations with thunderstorms have also been studied in details [16,25–29].

To discover more valuable information, a few simulations have been done to study the intensity and energy changes of secondary particles during thunderstorms [17,30–32]. Buitink et al. [33] have modified the CORSIKA code and performed simulations to calculate the effect of an electric field on the development of proton showers with energies more than $10^{16}$ eV. Their results showed that the RREA might occur at high altitudes.

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From the experimental observations and simulation results above, it seems that these enhancements of secondary particles during thunderstorms are correlated with the electric field and the RREA will occur under certain conditions. However, the acceleration mechanisms of secondary charged particles caused by atmospheric electric field still remain unresolved.

In 2011, the AGILE team found that the TGF emission above 10 MeV had a significant power-law spectrum with energies up to 100 MeV [34]. These results posed a big challenge for the widely accepted TGF model based on the RREA mechanism.

It is clear now that intensity decreases for the hard component of cosmic rays are associated with thunderstorms electric field. Chilingarian et al. [15] found a deficit of ~6.0% in the flux of muons with energies greater than 200 MeV during thunderstorms. By analyzing the data from the Carpet air shower array, Alexeenko et al. [11] studied the effects of thunderstorms electric field on the soft and hard components of cosmic rays separately. The net effect is a decreasing intensity for the hard component (muons) and an increasing intensity for the soft component (electrons). Interestingly, a negative correlation of variations between the electric field and the soft component intensity was reported in the same paper. That is to say, the intensity of the soft component decreased in a certain range of positive fields. The study suggested that the reason for this decreasing phenomenon was the poor separation of the soft and hard components. Is the soft component intensity decrease related to thunderstorms electric field or poor separation of the components?

The intensity changes of ground cosmic rays were detected by the ARGO-YBJ experiment, which is connected to two independent data acquisition systems, corresponding to the shower and scaler operation modes. The total counts of charged particles, namely multiplicity (n), are measured every 0.5 s in scaler mode. There are four independent channels to record the counting rates referred to $n \geq 1, 2, 3, 4$, respectively. More details about the ARGO-YBJ detector can be found elsewhere [35]. During thunderstorms, the increases for channel $n=1$ or $n=2$ are detected. But if $n=3$ or $n \geq 4$, the counting rates do not obviously change or even decline [36–38]. The intensity decreases cannot be explained by the RREA mechanism. Are these decreasing phenomena associated with thunderstorms electric field? Moreover, what is the acceleration mechanism for them?

Because of the unknown strength and structure of thunderstorms electric field, there are numerous problems regarding the processes of high-energy particle interactions in the atmosphere that remain unsolved to this today. In order to learn more about the acceleration mechanism and the intensity change, more theoretical, experimental and careful simulation results are needed.

In this work, we perform Monte Carlo simulations by using CORSIKA to study the effect of a near-earth electric field on the intensity of ground cosmic ray positrons/electrons at YBJ. Using these simulations, we then try to analyze the cause of the decreasing phenomena for soft components. This paper is organized as follows: The simulation parameters are introduced in Section 2. The simulation results of vertical and inclined proton showers with several different primary energies are shown in Section 3. The discussions are presented in Section 4. The conclusions are given in Section 5.

## 2. Simulation parameters

CORSIKA (COsmic Ray SImulations for KAscade) is a detailed Monte Carlo program used to study the evolution and properties of extensive air showers in the atmosphere [39]. In our simulation work, we use the code of CORSIKA 7.3700, its subroutine ELECTR has been extended to account for the effect of atmospheric electric fields on the transport of electromagnetic particles. The extension follows the programming procedure emf_macros.mortran, which was developed by Bielajew [40]. The selected hadronic interaction model is QGSJETII-04 for high energy and GHEISHA for low energy.

Previous studies have shown that the atmospheric electric field distributed roughly within the altitude scope of 4−12 km during thunderstorms [41]. Because charged secondary particles will lose their energies quickly through radiation and ionization, the effect on the intensity of charged particles can be neglected in the electric field, which is far from detectors. More details can be found elsewhere [42]. In our simulations, the electric field length is 2000 m, from an altitude of 6300–4300 m (corresponding to the atmospheric depth 484–606 g/cm$^2$). From the data detected by two electric field mills (Boltek EFM-100) which are installed on the roof of ARGO-YBJ building, we found that the strength of near-earth thunderstorms electric field at YBJ is mostly within 1000 V/cm [43]. In our work, the uniform electric field ranges from −1000 to 1000 V/cm. Here, we define the positive electric field as one that accelerates positrons downward in the direction of the earth.

According to the energy threshold of the ARGO-YBJ detector, which is a few tens of GeV in scaler mode and a few hundreds of GeV in shower mode [35], proton showers with three typical energies of 30, 100 and 770 GeV are chosen as the primary particles in this work.

Since positrons and electrons predominate in the secondary charged particles of cosmic rays, and the hadronic and muonic parts of the shower are hardly affected, the effects of the electric field on positrons and electrons are properly taken into account in our work. In view of the acceleration of the field, the energy cutoff is set to 0.1 MeV, below which value positrons and electrons are discarded from the simulation.

To minimize the fluctuations from shower to shower, we use the same line just like the paper [33]. The differences derived from the first interactions are predominated for extensive air showers. INTTEST option in CORSIKA was selected to simulate the first interaction. All secondary particles after the first interactions were listed in a file, which can be used as an input stack for CORSIKA using the STACKIN option. In this work, we use INTTEST option to make ten thousand shower simulations for vertical and inclined showers with primary energy 30, 100 and 770 GeV. The shower with a large number of secondary particles in the first interaction and a fairly typical longitudinal shower profile was selected. Then we use the selected shower as the input of STACKIN option to generate $2 \times 10^6$ showers with different random seeds. This will produce much smaller variations.

## 3. Simulation results

When a primary cosmic ray enters the atmosphere, it will produce a large number of secondary particles via the hadron and electromagnetic cascades. These particles are distributed in a range many kilometers wide. This phenomenon is called extensive air shower (EAS). The total number of secondary particles, which are produced in an EAS at a particular level in the atmosphere, is called the shower size. In this paper, we only consider the effect of an electric field on positrons and electrons. The shower size is defined as the total number of positrons and electrons.

### *3.1. Vertical showers with primary energy 100 GeV*

The electric fields are chosen as a series of values in the range of −1000−1000 V/cm. The correlations between the number of positrons/electrons and the near-earth electric field are simulated. Fig. 1 shows the percent change of the average number of