

Theoretical investigation of thunderstorm induced enhancements of cosmic ray fluxes

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ABSTRACT

We conducted theoretical investigation of long lasting pulses of cosmic-ray electrons and gamma-ray radiation, which are often observed during thunderstorms by particle detectors at high altitude cosmic-ray stations. These thunderstorm ground enhancements (TGEs) last several minutes, during which the flux of electrons and gamma-quants can surpass a few hundred percent over background level. We developed theoretical model and derived energetic spectrums of electrons and gamma-quants at given value of thunderstorm electric field. The model considers two following mechanisms, which can change the flux of electrons in electric field: (i) transformation of the spectrum of cosmic-ray electrons and (ii) formation of electron avalanche. Due to (i) the number of low (few MeV) energy electrons decreases and small abundance (<5% of total flux of cosmic rays) of cosmic-ray electrons with energies >10 MeV emerges. The spectral fluxes of two electron components – avalanche and cosmic-ray electrons are derived, which shows that contribution of cosmic-ray electrons in total abundance of electrons is small. Consequently, the contribution of gamma ray radiation, produced by the abundance of cosmic-ray electrons is small as well. We derived the exact equations for the spectrums of these two components of gamma ray radiation and showed that spectral curve of avalanche gamma-quants can be approximated by a simple function $\exp(-E/E_0)/E$ up to ~ 40 MeV. At higher energies gamma-ray radiation is produced by the abundance of cosmic-ray electrons and it has approximately power-law spectrum.

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1. Introduction

The possibility of arising gamma ray radiation during thunderstorms was proposed by Wilson [1]. He predicted that in electric field of thunderclouds electrons can be accelerated to great energies and produce radiation via bremsstrahlung mechanism. After 70 years such a radiation were discovered and studied in spacecraft observations first by BATSE CGRO [2], then in more details by RHESSI [3], AGILE [4] and FERMI [5] spacecraft. TGFs are upward directed intense milli, microsecond pulses of gamma-quants, associated with lightning discharge. Energetic spectrum of TGFs extends up to ~ 40 MeV, being exponentially decaying.

Apart from TGFs, long lasting enhancements of cosmic ray fluxes, have been often registered during thunderstorms by ground based detectors at high altitude cosmic-ray stations [6–14]. Following Chilingarian et al. [13] they are called below thunderstorm ground enhancements (TGEs). TGEs last from a few to dozen minutes, during which particle fluxes can exceed the background level up to a few hundred percent. Since electrons suffer from strong absorption while moving through atmosphere, mostly gamma-

quants reach to the ground, and therefore TGEs registered by ground-based detectors, are caused mainly by gamma ray radiation.

There are similarities and differences between TGF and TGE. Both gamma-ray radiations are produced via bremsstrahlung mechanism by the avalanche of energetic electrons, formed in electric field of thunder clouds. Theory of this process, called runaway breakdown (RB) has developed by Gurevich et al. [15]. However, while there is a consensus about the nature of TGF, the TGE phenomenon is not yet clearly understood. Investigations of TGE during the last decade showed that they cannot be caused by variations of cosmic-ray muons fluxes (estimated in [16]). Present consensus about the nature of TGE implies that two processes, arising in electric field, are responsible for TGE [9,10,16]: (i) transformation of energetic spectrum of cosmic-ray electrons and (ii) origination of electron avalanche when electric field surpasses some critical value. Our goal in this paper is developing of theoretical model of TGE, based on these processes and clarifying its main feature – energetic spectrums of TGE electrons and gamma-quants.

In sec.1 we develop theoretical model describing energetic spectrum of electrons in electric field due to transformation of their spectrum and due to formation of avalanche, in Section 2 the spectral fluxes of gamma rays, produced by these two

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components of electrons are derived, in Section 3 we discuss experimental results and form conclusions by briefly presenting obtained results.

2. Spectral flux of TGE electrons

In this paragraph we investigate the flux of energetic electrons in atmosphere in the presence of electric field. The influence of electric field on the flux of electrons is twofold. First, electric field redistributes electrons by energies, changing their energetic spectrum. Second, some secondary electrons, which are continuously produced due to ionization of air atoms, now in the presence of electric field can be accelerated and knocking out new electrons, form the avalanche. Both effects will lead to the abundances of electrons and gamma rays, which are observed often at high altitude cosmic-ray stations as impulsive increase in counting rates of particle detectors.

Theoretical modeling of these two processes should be based on dynamics of electron movement in the air. The energetic electrons can undergo several interactions as they travel through the atmosphere: ionization, bremsstrahlung, Compton scattering, annihilation etc. One way to represent the net effect of these interactions is to consider the drag force experience by an energetic electron. For ionization and bremsstrahlung processes, which are predominant, the drag forces as a function of electron kinetic energy E are determined as the following

$$F_{ion}(E) = \frac{4\pi e^4 Z n}{m v^2} \left(\ln \left(\frac{2mc^2 \beta^2}{J(1-\beta^2)} \right) - \beta^2 \right) \quad (1)$$

$$F_{br}(E) = 4\alpha r_e^2 Z(Z+1)nE \ln \left(\frac{2E}{mc^2} + \frac{5}{3} \right) \quad (2)$$

Here m and e are the mass and charge of electron, $Z \sim 14$ is the mean number of electrons in the molecule of air, $\alpha = e^2/\hbar c$ is the fine structure constant, $\hbar$ is the Plank constant, $r_e = e^2/mc^2$ is the classical radius of electron, c is the speed of light, v is the speed of electron, n is the number density of air molecules, $J \sim 80$ eV is the mean ionization potential for air atoms.

Total drag force $F_{ion} + F_{br}$ versus electron kinetic energy is presented in Fig. 1 along with arbitrary choosed electric force from thunder cloud electric field (which does not depend on the energy of the electron).

If electric force surpasses the minimal value of drag force, the total force exerting on electron accelerates it in some interval of

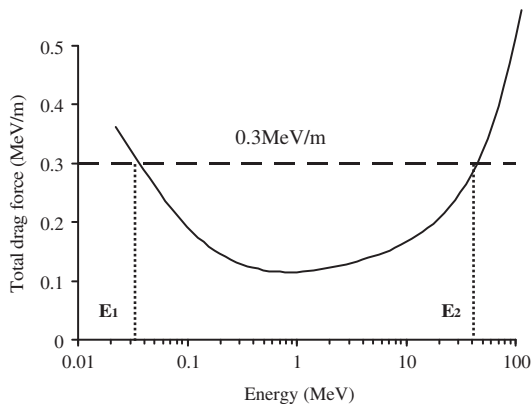


Fig. 1. Total drag force $F_{ion} + F_{br}$, experienced by electron, moving in atmosphere at the altitude 3600 m. It gets minimum $F_c \sim 0.14$ MeV/m at kinetic energy of electron of about 1 MeV. The horizontal dashed line shows electric force from electric field 0.3 MV/m, which intersects the curve of drag force at energies $E_1 \sim 0.03$ MeV and $E_2 \sim 40$ MeV. In energy range $E_1 < E < E_2$ electric force surpasses total drag force.

energies $E_1 < E < E_2$, as it is clear from Fig. 1. Number of electrons in this energy interval increases, due to RB and as a result the relativistic runaway electron avalanche (RREA) is formed. For triggering the downward avalanche it is necessary to have seed electrons with energies above ~ 0.1 MeV. Cosmic-ray electrons can successfully play their role. Each such cosmic-ray electron will trigger the avalanche of secondary electrons and as a result the flux of avalanche electrons will increase with propagation distance L as $B(\exp(L/L_a) - 1)$, where L_a is the avalanche e-folding length, B is the total flux of cosmic-ray electrons at the start of avalanche, i.e. number of cosmic-ray electrons traversing downward unit area during unit time. Avalanche e-folding length L_a depends on the amplitude of electric field. Numerical analysis (e.g. [17,19,20]) gave approximate equation $L_a \sim 7.3 \text{ MV}/(F - 0.27 \text{ p})$, where F is the electric field in MV/m, p is the air pressure in atmosphere. For the altitudes ~ 3000 – 3500 m and electric field ~ 0.3 MV/m, the avalanche length is about 80 m.

Spectral distribution of avalanche electrons also has been simulated numerically by Monte-Carlo method [17–22]. It was found that in energy range from few to about 80 MeV this spectrum is close to exponent $\exp(-E/E_0)$, with e-folding energy $E_0 \sim 2$ – 7 MeV. The energy E_0 is formally the mean of exponential distribution $\exp(-E/E_0)$, therefore it is the mean energy of avalanche electrons. Mean energy E_0 is almost independent from the value of electric field for the fields larger than ~ 0.3 MV/m, however it decreases to ~ 2 – 4 MeV for smaller amplitudes of electric field [17–20]. It should be noted that the relation of E_0 to other physical quantities is yet unknown. We know neither what parameters of atmosphere determine the value of E_0 , nor how E_0 depends on these parameters quantitatively. This problem is out of scope of the present research, so here we just use the known value of $E_0 \sim 7$ MeV as a given parameter.

Thus, due to formation of avalanche, the abundance of electrons is raised at the distance L , with spectral density written as the following

$$A_{ea}(L, E) = B(\exp(L/L_a) - 1) \exp(-E/E_0)/E_0 \quad (3)$$

Note, that used model of drag force implies that electrons cannot gain energy larger than E_2 (see Fig. 1). However, since the process of energy losing by electrons has random nature, some electrons can gain energy larger than E_2 before losing it. Hence, one can assume that Eq. (3) is valid at energies somewhat higher than E_2 .

Integrating (3) over energies larger than threshold energy of detector E_{th} (one should assume that E_{th} is smaller than E_2) we obtain total number of avalanche electrons with energies larger than E_{th}

$$\begin{aligned} I_{ea} &= \int_{E_{th}}^{E_2} A_{ea}(L, E) dE \\ &= B(\exp(L/L_a) - 1)(\exp(-E_{th}/E_0) - \exp(-E_2/E_0)) \end{aligned} \quad (4)$$

Thus, the avalanche mechanism provides large abundance of electrons with exponential spectrum up to several dozen MeV energies, depending on the amplitude of electric field.

Now we will investigate the first mechanism – transformation of cosmic-ray electron spectrum, which can give the abundance of electrons as well. Suppose that electric field extends up to the altitude z_2 . Electron spectral flux at the altitudes z above z_2 is well known, let define it as $s_0(z, E)$. It is a power-law function, that can be taken from conventional EXPACS database [23], so our goal is to obtain it at lower altitude $z_1 < z_2$. Total flux of electrons B is calculated by integrating $s_0(z, E)$ over energies above 1 MeV (e.g. for the altitude 3600 m it is obtained $B \sim 12,000 [1/(m^2 \text{ min})]$).

First let us consider how the flux of electrons changes propagating from the altitude z_2 to the altitude z_1 .

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