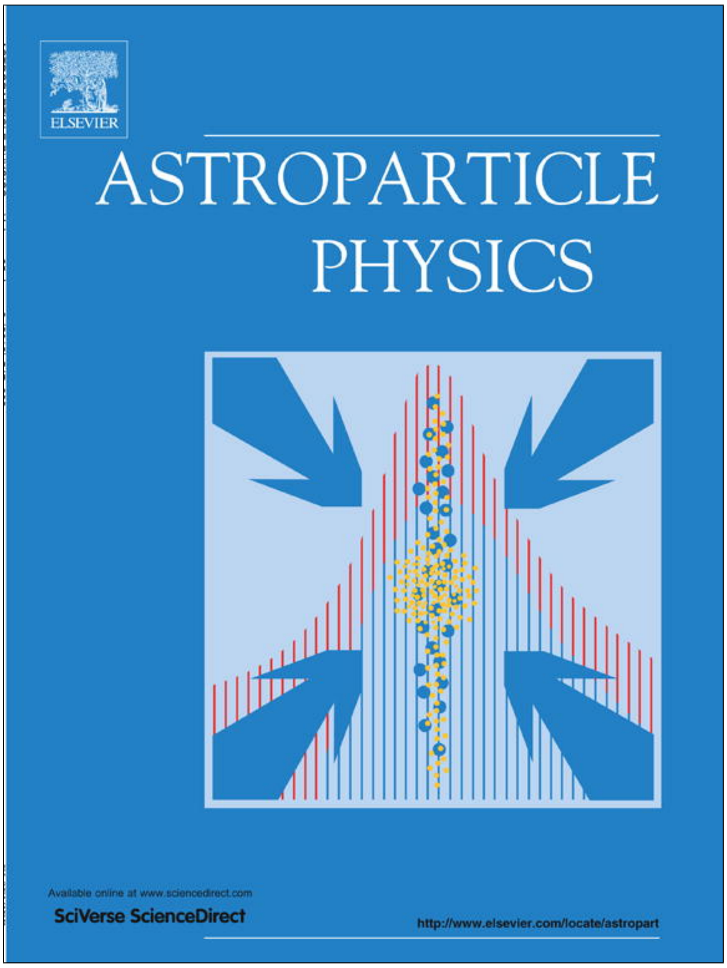
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Theoretical investigation of thunderstorm induced enhancements of cosmic ray fluxes

G.G. Karapetyan

Cosmic Ray Division, Yerevan Physics Institute (Alikhanian National Lab), Yerevan 0036, Armenia

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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.

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 excess 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 comic-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

E-mail address: grigori@mail.yerphi.am

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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

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

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

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 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 $L_a \sim 7.3$ MV/($F - 0.27$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 - ~ 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 loosing 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}

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

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 $B \sim 12{,}000[1/(\mathrm{m}^2\,\mathrm{min})]$).

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

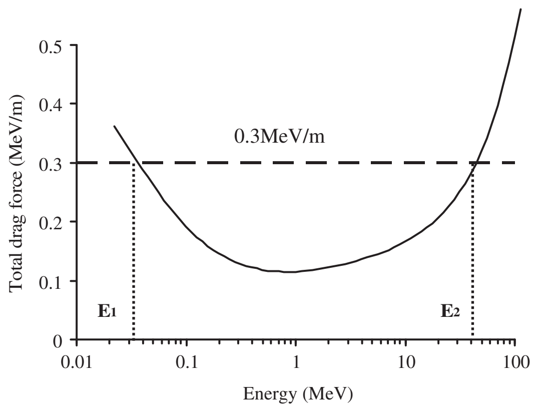

Fig. 1. Total drag force $F_{ion} + F_{br}$, experienced by electron, moving in atmosphere at the altitude 3600 m. It gets minimum $F_c \sim 0.14$ MeV/m at kinetic energy of electron of about 1 MeV. The horizontal dashed line shows electric force from electric field 0.3 MV/m, which intersects the curve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

In the presence of electric field electron with energy up to E_2 will acquire some additional energy from electric field, when propagating downward to the altitude z_1. Consequently, the number of electrons with given initial energy, say E, will increase due to additional lower energy electrons, which will be accelerated and get energy E by arriving at the altitude z_1. In terms of spectral curves it means that each point of electron spectral curve is shifted to the right in the presence of accelerating electric field. In the absence of drag force the change in energy of each electron would be $e\phi$ (ϕ is the potential difference between z_1 and z_2), so that each point of spectral curve will be shifted to the right on the same amount $e\phi$. However, since drag forces (1), (2) depend on electron energy, this shift actually will be different for different points. Moreover, up to energy E_2 the spectral curve will shift to the right (because of acceleration of electrons), whereas above the energy E_2 it will shift to the left (because electrons with energy larger than E_2 will be decelerated). For proper accounting of this effect one should derive the relationship between the final and initial energies of electron, passing in electric field from the altitude z_2 to z_1. This relationship is obtained by the solution of the equation of motion

$$\frac{dE(z)}{dz} = F_{ion}(z, E(z)) + F_{br}(z, E(z)) - f(z) \qquad (5)$$

where coordinate z denotes the altitude above sea level, F_{ion} and F_{bg} are determined by the Eqs. (1), (2) where air density depends on the altitude as $n(z) = n_0 \exp(-z/9100\,\text{m})$, $n_0 \sim 2.7 \times 10^{19}$ (1/cm^3) is number density of air molecules at sea level, $f(z)$ is electric force, acting downward on electrons.

Eq. (5) is the first order differential equation, for which we must determine the value of initial energy at the altitude z_2:$E(z_2)$. Then by solving Eq. (5), one can present the final energy of electron $E(z_1)$ at the altitude z_1 versus the initial energy E_2 at the altitude z_2 as the following:

$$E(z_1) = E(z_2) + g(z_2 - z_1, E(z_2)) \qquad (6)$$

where $g(z_2 - z_1, E(z_2))$ is the gain of electron energy when the electron passes from the altitude z_2 to the altitude z_1.

This function, calculated from (6) e.g. for $z_1 = 3600$ m, and $z_2 = 3700$ m is shown in Fig. 2. It is seen that in the presence of electric field, the gain of energy is positive for electrons having initial energy up to $E_2 \sim 40$ MeV and is negative for higher energy electrons. However, in the absence of electric field, the gain of energy for all electrons is negative. By this electrons with initial energies smaller than $\sim$20 MeV lose all energy somewhere between z_1–z_2 and they do not reach the altitude z_1.

Hence by having initial spectrum of electron flux $s_0(z_2,E)$ at the altitude z_2, one can derive the spectrum $s(z_1,z_2,E)$ at lower altitude z_1 by shifting this spectrum to the amount $g(z_2 - z_1,E)$ as the following

$$\begin{array}{ll} s(z_1, z_2, E) = s_0(z_2, E - g(z_2 - z_1, E(z_2))) & \text{if} \quad E - g(z_2 - z_1, E(z_2)) > 0 \\ s(z_1, z_2, E) = 0 & \text{otherwise} \end{array} \qquad (7)$$

Thus the shift of electron energy when it passes from the altitude z_2 to altitude z_1 is given by the function $g(z_2 - z_1,E)$ and not by $e\phi$.

By using Eqs. (5)–(7) we calculated spectral fluxes of electrons at lower altitudes, when initial flux with the spectrum $s_0(3700,z)$ falls from the altitude 3700 m. Appropriate curves are presented in Fig. 3. It is seen that spectral curves at lower altitudes in the presence of electric field are transformed as proposed above: at energies up to $E_2 \sim 40$ MeV they are shifted to the right, because of acceleration of these electrons, and they are shifted to the left at higher energies, since those electrons are decelerated. Due to this transformation, the abundance of electrons at energies below $\sim$40 MeV, and a deficit of electrons at energies above 40 MeV are formed, comparing to initial flux. Note that spectral curves drop when approaching low energies. This takes place because all small energy electrons from initial flux, acquire additional energy from electric field, so that number of small energy electrons decreases to zero. For example, after passing 100 m, only electrons with energies larger than about 10 MeV will be presented in final flux (it is seen also in Fig. 2, where electrons with initial energy $\sim$1 MeV get final energy $\sim$10 MeV after propagating the distance 100 m).

Thus we took cosmic-ray electron flux at the altitude z_2 and calculated how it changes at lower altitude z_1 in the presence of electric field. However, such a simplified model does not provide yet actual spectrum of cosmic-ray electrons at the altitude z_1 in the presence of electric field, because we did not account newly born electrons in the slab $z_1 < z < z_2$, which contribute to total flux at z_1 as well. The spectrum of newly born electrons is close to $s_0(z,E)$, therefore newly born at the altitude, say z_3, electrons will have at the altitude z_1 the spectrum, given by the function (7) with z_3 instead z_2. Thus to account for the contribution from all newly borne in the slab z_1–z_2 electrons, one should sum functions (7), in the result the spectrum of cosmic-ray electrons $S(z_1,E)$ at the altitude z_1 is determined as

$$S(z_1, E) = \frac{1}{N}\sum_{i=1}^{N} s\left(z_1, z_1 + \frac{i}{N}(z_2 - z_1), E\right) \qquad (8)$$

where N should be taken to provide length step about meter.

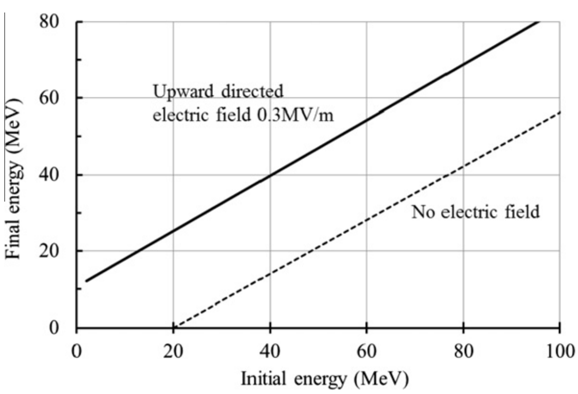

Fig. 2. Final energy of electron passing downward 100 m from the altitude 3700 m in the absence (dashed line) and the presence (solid line) of upward directed electric field 0.3 MV/m.

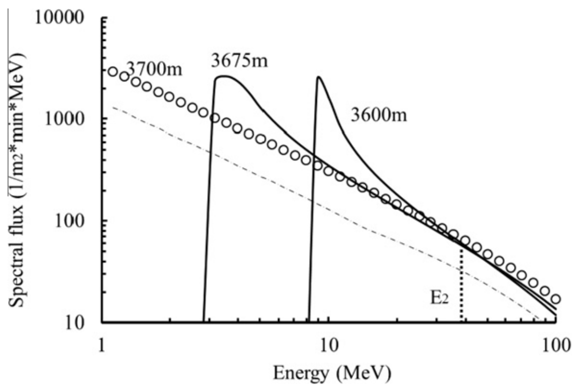

Fig. 3. Spectral fluxes of electrons in upward directed electric field 0.3 MV/m at different altitudes (solid lines). Initial flux with the spectrum $s_0(3700,E)$ (open circles) falls from the altitude 3700 m. The dashed line is spectral flux at 3600 m in the absence of electric field. The dotted line marks energy $E_2 \sim 40$ MeV, at which total drag force is compensated by electric force 0.3 MeV/m, as it is seen in Fig. 1

The graphs of $S(z,E)$, calculated by (8) are presented in Fig. 4

Unlike to Fig. 3 here the spectrums extend to low energy range as well. This takes place due to newly born low energy electrons, coming from the altitudes near z_1: these electrons acquire smaller energy in electric field and consequently they contribute to lower part of spectrum. If electric field decreases the spectrum (8) will tend to usual cosmic-ray electron spectrum $s_0(z,E)$ as it is seen in Fig. 5

By extracting from (8) the flux of cosmic-ray electrons in the absence of electric field $s_0(z_1,E)$, we obtain spectral flux of abundance of cosmic-ray electrons $A_{ec}(z_1,E)$ at the altitude z_1, originating due to the presence of electric field

$$A_{ec}(z_1,E) = S(z_1,E) - s_0(z_1,E) \tag{9}$$

The graphs of A_{ec} are presented in Fig. 6 along with the graphs of avalanche electrons derived from (3). It is seen that for the altitude <3400 m the abundance of avalanche electrons strongly surpasses that of cosmic-ray electrons. However the flux of avalanche electrons rapidly decreases at high energies due to exponentially decaying spectrum, meanwhile the abundance of cosmic-ray electrons extend to $\sim$100 MeV and higher. Such behavior of spectrums of electrons and gamma-quants was derived in [13] by Monte-Carlo simulations.

Integrating A_{ec} in (9) over energies, say 10 MeV, we obtain total abundance of electrons, with energies >10 MeV. In Fig. 7 there are presented these total abundances of cosmic-ray and avalanche electrons. The last is given by Eq. (4), where the approximated value $L_a \sim 80$ m is used.

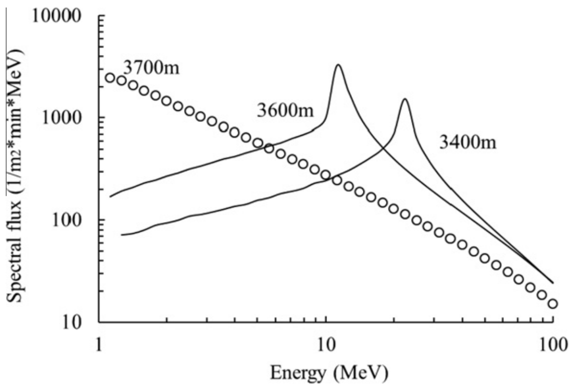

Fig. 4. Spectral fluxes of cosmic-ray electrons at different altitudes in the presence of upward directed uniform electric field 0.3 MV/m extending up to the altitude 3700 m. The open circles are cosmic-ray electron spectrum at the altitude 3700 m, given by the function $s_0(3700,E)$.

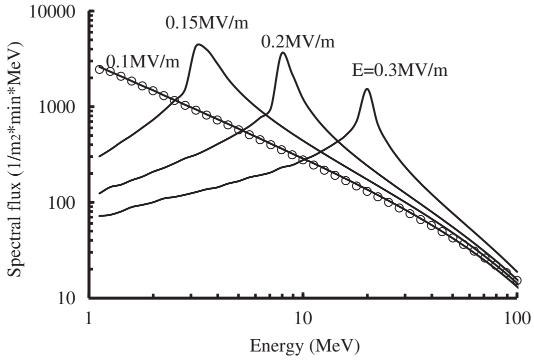

Fig. 5. Spectral fluxes of cosmic-ray electrons at the altitude 3400 m at different values of upward directed electric field, extending up to the altitude 3700 m. The open circles are cosmic-ray electron spectrum at the altitude 3700 m, given by the function $s_0(3700,E)$.

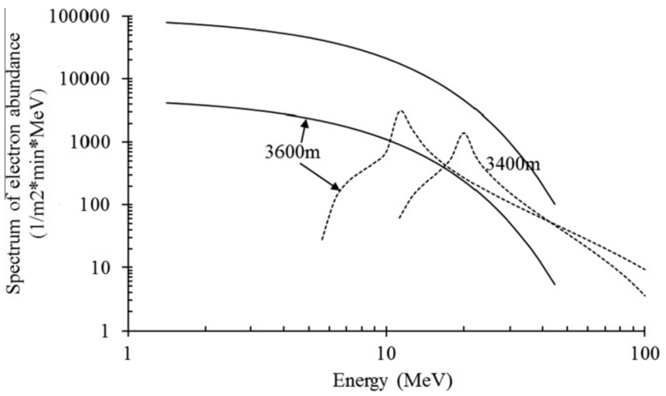

Fig. 6. Spectral fluxes of avalanche (solid lines) and cosmic-ray (dotted lines) electron abundances at the altitudes 3400 and 3600 m, in the presence of upward directed electric field 0.3 MV/m, extending up to 3700 m.

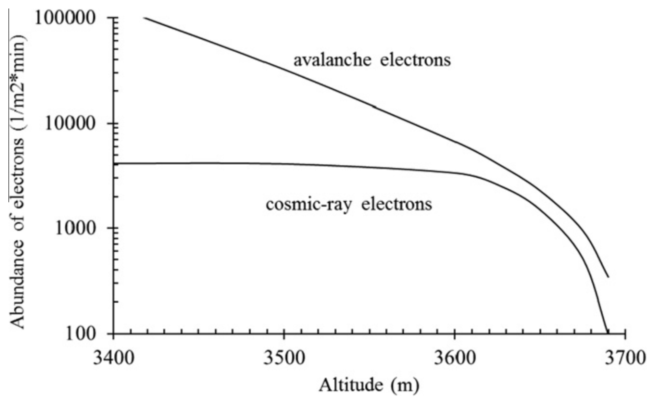

Fig. 7. Total abundances of cosmic-ray and avalanche electrons with energies >10 MeV at different altitudes in the presence of upward directed electric field 0.3 MV/m, extending up to the altitude 3700 m.

It is seen that the abundance of cosmic-ray electrons is limited by the value $\sim$4200(1/m^2 min), which is about 35% of total electron flux $B \sim 12{,}000$(1/m^2 min).

By using EXPACS one can estimate that for $E > 10$ MeV, the contribution of cosmic-ray electrons in total flux of cosmic rays is about 15%, therefore the increase of cosmic-ray electrons flux by 35% due to transformation of the spectrum will cause about 35% $\times$ 15% $\sim$ 5% enhancement in total cosmic ray flux. However, it should be taken into account that along with the acceleration of electrons, the stopping of positrons will take place which will shift to the left the spectral curve of positrons, consequently decreasing positron flux. In the result the enhancement of total cosmic ray flux due to transformation of cosmic-ray electron spectrum will be smaller than 5%. Hence one can conclude that the abundance of avalanche electrons dominates over the abundance of cosmic-ray electrons.

Thus we presented spectral flux of electron abundance, arising in the presence of electric field as the sum of cosmic-ray and avalanche electron abundances

$$A_e(z,E) = A_{ec}(z,E) + A_{ea}(z,E), \tag{10}$$

determined by the Eqs. (9) and (3) correspondingly.

We want now to derive the intensity of gamma ray radiation, produced by these abundances of electrons.

3. Spectral flux of TGE gamma rays

To derive the spectral flux of gamma ray radiation, one should use cross section of photon bremsstrahlung, when energetic electron interacts with nuclei of atom. Let define E the initial energy of electron and E_f its final energy after emission of gamma quanta. Since electron mass is negligibly small comparing with the mass of nuclei, the energy of emitted gamma quanta is $\hbar\omega = E - E_f$. We are interested in gamma-quants, which are emitted by ultra relativistic electrons, so that the following conditions are fulfilled

$$E >> mc^2, E_f >> mc^2 \quad \text{and} \quad \hbar\omega >> mc^2, \tag{11}$$

where mc^2 = 0.51 MeV is the rest energy of electron.

The bremsstrahlung cross section in this range of energies is given by the equation [24]

$$d\sigma_\omega(E) = 4Z^2\alpha r_e^2 \frac{d\omega}{\omega}\left[1 - \frac{2E_f}{3E} + \frac{E_f^2}{E^2}\right]\left[\ln\left(\frac{2EE_f}{mc^2\hbar\omega}\right) - \frac{1}{2}\right]. \tag{12}$$

At high energies of electron, the screening correction should be applied to (12), which accounts for the decrease of electric potential of the nuclei by atomic electrons. Complete screening takes place when logarithm in (12) surpasses the value about 4 [24]. Hence to account this effect we will replace the logarithm in (12) by the factor 4, as soon as it surpasses 4.

By multiplying cross section (12) on spectral flux of electrons and number density of air atoms and then integrating it over all electrons, having energy larger than energy of gamma quanta we come to the spectral flux of gamma-quants, produced by electrons from unit length. Integrating this quantity over propagation length L, we obtain total spectral flux of emitted gamma-quants $A_g(L,E)$

$$A_g(L,E)dE = n\int_0^L dz \int_E^\infty d\sigma_\omega(E')(A_{ec}(z,E') + A_{ea}(z,E'))dE'. \tag{13}$$

After some transformations (14) is written as the following

$$A_g(L,E) = \int_0^L A_{gc}(z,E)dz + (L_a \exp(L/L_a) - L_a - L)A_{ga}(E) \tag{14}$$

where

$$A_{gc}(z,E) = \frac{k}{E} \times \int_E^\infty \left[\frac{4}{3} - \frac{4E}{3E'} + \left(\frac{E}{E'}\right)^2\right]\left(F(E',E) - \frac{1}{2}\right)A_{ec}(z,E')dE', \tag{15}$$

$$A_{ga}(E) = \frac{Bk}{E_0 E} \times \int_E^\infty \left[\frac{4}{3} - \frac{4E}{3E'} + \left(\frac{E}{E'}\right)^2\right]\left(F(E',E) - \frac{1}{2}\right)\exp\left(-\frac{E'}{E_0}\right)dE'. \tag{16}$$

Here screening function $F(E',E)$ is determined as

$$F(E',E) = \ln\left(\frac{2E'(E'-E)}{mc^2E}\right) \text{ if } \ln\left(\frac{2E'(E'-E)}{mc^2E}\right) < 4 \tag{17}$$

and $F(E',E)$ = 4, otherwise, $k = 4Z^2\alpha r_e^2 n$.

Thus we presented the flux of gamma-quants as the sum of two terms. First term in (14) – with $A_{gc}(E)$ describes gamma ray radiation, produced by the abundance of cosmic-ray electrons and second term – with $A_{ga}(E)$ by the avalanche electrons.

As shown above the main part of TGE electrons are avalanche electrons, so that the main part of gamma ray radiation is expected to be the avalanche gamma-quants, i.e. the main contribution to total flux of gamma ray radiation (14) gives second term with A_{ga}. Really, in Fig. 8 spectral fluxes of gamma ray radiation are presented at the altitude 3400 m, produced by both avalanche and cosmic-ray electrons, calculated by Eqs. (14)–(16). Upward directed electric field extends up to 3700 m, so that electron avalanche begins at that altitude and grows by downward propagation. It is seen that main part of TGE flux is comprised by the avalanche gamma-quants. However avalanche curve rapidly decays at high energies, consequently a "tail" of high energy gamma-quants, produced by bremsstrahlung of cosmic-ray electrons (Eq. (15)) remains in TGE spectrum. The tail can be fitted by power-law function. Thus we can conclude that strong and moderate TGEs are caused by the avalanche gamma ray radiation.

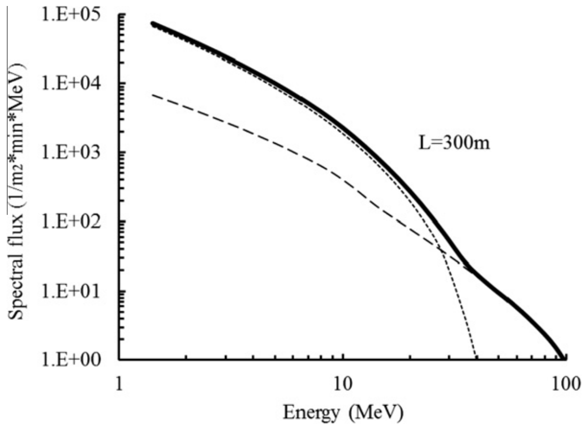

Fig. 8. Spectral fluxes of gamma ray radiation at the altitude 3400 m, calculated by Eqs. (13)–(16). Upward directed electric field 0.3 MV/m extends up to 3700 m. The dashed and dotted lines correspond to gamma ray radiation, produced by cosmic-ray and avalanche electrons respectively; the thick solid line is their sum.

Spectral flux of these avalanche gamma-quants is described by the Eq. (16). This equation has rather complicated form and the behavior of spectrum is not pronouncedly seen there. However the integral in (17) can be simplified, by assuming that logarithmic function is nearly constant quantity being ~2.3. Then by introducing integral exponential function $E_1(x)$, determined as [25]

$$E_1(x) = \int_x^\infty \frac{\exp(-t)}{t}dt, \tag{18}$$

the approximate expression for $A_{ga}(E)$ is derived as the following

$$A_{ga}(E) \sim \frac{2.3Bk}{E}\left(1 + \frac{4E_0}{3E}\right)\exp\left(-\frac{E}{E_0}\right)\left(1 - \frac{E}{E_0}\exp\left(\frac{E}{E_0}\right)E_1\left(\frac{E}{E_0}\right)\right) \tag{19}$$

Using asymptotic of function $E_1(x)$ [25] one can further simplify the Eq. (19) and obtain in the result the simple equation

$$A_{ga}(E) \sim \frac{2.3Bk}{E}\exp\left(-\frac{E}{E_0}\right) \tag{20}$$

This equation shows that spectrum of avalanche gamma-quants is power-law with power index 1 up to energies $\sim E_0$ and it becomes exponentially decaying at higher energies. The Eq. (20) is convenient for using instead of exact integral (16), or approximate (19) expressions. All three Eqs. (16), (19), and (20) give spectral curves, which are close to each other, as it is seen in Fig. 9.

4. Discussion, conclusions

Thus we derived analytically spectral fluxes of TGE electrons and gamma-quants and showed that main contribution in TGE particles give avalanche gamma-ray radiation. We presented the spec-

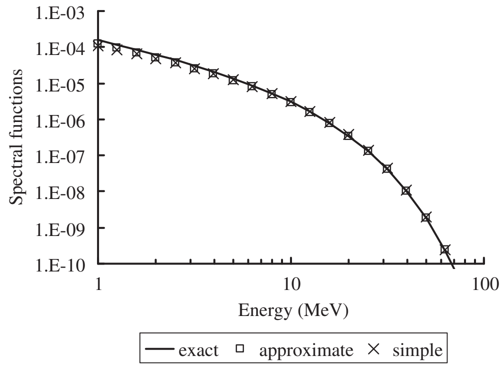

Fig. 9. Spectral function of avalanche gamma rays, calculated by exact (17), approximate (21) and simple (22) equations with $B = 1$.

tral flux of this gamma-ray radiation by the simple function (20), which is exponentially decaying at energies $>E_0$. This spectrum extends up to energy $\sim$40 MeV. At higher energies the TGE gamma ray radiation is produced by the abundance of cosmic-ray electrons with close to power-law spectrum. The experimental data of TGE particle spectrums until recently have been obtained for low energy interval ([11], [12]). In these experiments the spectrums of gamma-ray radiation extend up to $\sim$10 MeV, being power-law, however the behavior of spectrum above 10 MeV was remained unknown. Recent investigations [13,14] clarified the spectrums of electrons and gamma-quants at higher energies. In [13] the authors have investigated particle spectrums of two TGEs by newly installed special particle detectors at the Aragats Space Environmental Center (3200 m above sea level). Electron spectrum was obtained by direct measurements of electron flux at different energies, whereas the spectrum of gamma-quants was recovered from the solution of inverse problem by using special procedure of energy deposits histograms. The mean energy of avalanche electrons and gamma-rays in those two TGE events is estimated to be $\sim$3–4 MeV, and the electric field amplitude – to be about 0.2 MV/m. These experimental data are in qualitative agreement with theoretical models [17–20], predicting smaller than 7 MeV mean energy of electrons in weak (<0.3 MV/m) electric fields. Maximal energy of measured avalanche electrons ($\sim$25 MeV) also can be roughly estimated by intersection of electric force line (0.18 MeV/m) with drag force curve as it was done in Fig. 1 of present paper for 0.3 MeV/m electric force. Thus exponential spectrum of TGE avalanche electrons up to $\sim$25 MeV has proved in [13] by direct measurements. However the spectrum of TGE gamma-ray radiation was found to be power-law in 10–25 MeV interval, which is not consistent with exponential spectrum of electrons. It contradicts to Monte-Carlo simulation results as well as to the results of present paper (Eq. (16)), proving that flux of electrons with exponential spectrum produces gamma-ray radiation with exponential-like (Eq. (20)) and not power-law spectrum. Thus, predicted by theory exponential-like spectrum of TGE gamma-quants in interval $\sim$10–40 MeV is not yet confirmed by direct measurements.

In [14] the observational data and analysis of long (40 min) lasting TGE at Yangbajing Cosmic Ray Observatory (4300 m above sea level) are presented. The authors obtained spectrum of gamma-ray radiation at energies up to 160 MeV by direct measurements of particle fluxes at 4 different energies 40, 80, 120 and 160 MeV. They found that experimental data of gamma-ray radiation spectrum are fitted by power-law function with power index about 2. These results prove that the spectrum of TGE gamma-ray radiation at energies >40 MeV is described by power-law function, and it can extend up to energy $\sim$160 MeV. Earlier obtained results [11,12] showed that this spectrum at energies <10 MeV is power-law as well. Thus the behavior of TGE gamma-ray spectrum in middle energy interval $10\text{ MeV} < E < 40\text{ MeV}$ should be clarified in future experiments.

In conclusion, we obtained theoretically that:

- In the presence of accelerating electric field the spectrum of cosmic-ray electrons is transformed: number of low (few MeV) energy electrons decreases and small abundance (<5% of total flux of cosmic rays) of electrons with energies >10 MeV emerges
- Avalanche electrons dominate in total abundance of electrons, consequently strong and moderate TGEs are raised due to the avalanche gamma-quants, produced by bremsstrahlung of avalanche electrons
- The spectrum of avalanche gamma-quants is described approximately by the function $\exp(-E/E_0)/E$, with $E_0 \sim 3...7$ MeV, and it extends up to energy $\sim$40 MeV depending on the value of electric field
- At higher energies the flux of avalanche electrons and gamma-quants disappears and TGE is determined by a small portion of gamma-quants with near power-law spectrum, produced by a small abundance of cosmic-ray electrons.

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