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New type discharge generated in thunderclouds by joint action of runaway breakdown and extensive atmospheric shower

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Abstract

The kinetic theory of electric discharge in thunderclouds generated by runaway breakdown (RB) and extensive atmospheric shower (EAS) is developed. A giant growth of relativistic and thermal electrons, gamma and radio emission is predicted. The theory is compared with the recent results of EAS-radio experiments at Tien Shan mountains and with observations of lightning initiation process and narrow bipolar radio pulses. A reasonable agreement between the theory and observations is established. A new methods in cosmic ray physics is proposed: *RB detection* of extra high energy particles $\varepsilon_p > 10^{18}$ eV.

1. Introduction

Runaway breakdown (RB) is a new physical concept of an avalanche type increase of a number of relativistic and thermal electrons in air proposed by Gurevich et al. [1]. The avalanche can grow in electric field $E \geqslant E_c$ which is almost an order of magnitude less than the threshold of conventional breakdown. The electrons with high energies $\varepsilon \geqslant (0.1\text{–}1)$ MeV can become runaway and are accelerated under the action of electric field $E > E_c$. Directly this process—acceleration and collisions with air molecules lead to the avalanche type growth of the number of runaway and thermal electrons [2].

Runaway breakdown in air (RB) is stimulated by the presence of a high energy cosmic ray secondaries. Extensive atmospheric showers (EAS) are accompanied by an effective local growth of the number of cosmic ray secondaries and thus have a strong influence on the RB process [3]. The combined action of runaway breakdown

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and EAS lead to the development of RB-EAS discharge—new type of electric discharge where relativistic electrons play a decisive role. RB-EAS discharge is accompanied by strong exponential growth of the number of energetic and thermal electrons, positrons and gamma quanta. It can serve for the generation of a strong bipolar radio pulse [4].

The goal of the present work is to develop a theory of RB-EAS discharge. The theory would be compared with the existing experiments.

2. Kinetic equation

In real atmospheric conditions the thundercloud electric field is always inhomogeneous and according to balloon observations [5] has a layered structures. It means, that the field is inhomogeneous mainly along the height z: $E = E(z)$. Let us consider the Extensive Atmospheric Shower (EAS) passing through the thundercloud. Fast electrons generated during RB process in non-uniform electric field are described by relativistic kinetic equation which could be presented in the following form [6]:

$$\frac{\partial f}{\partial t} + p\mu\frac{\partial f}{\partial z} + eE(z)\left\{\mu\frac{\partial f}{\partial p} + \frac{(1-\mu^2)}{p}\frac{\partial f}{\partial \mu}\right\} = \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 F_D f\right) + \nu_\mu\frac{\partial}{\partial \mu}\left\{(1-\mu^2)\frac{\partial f}{\partial \mu}\right\} + S_I + Q_{\mathrm{EAS}}. \tag{1}$$

Here $f = f(t, p, \mu, z)$—the electron distribution function, μ—a cosine of an angle between direction of electric field $\mathbf{E}$ and momentum $\mathbf{p}$, F_D—friction force due to ionization,

$$F_D = Q_D\frac{\gamma^2}{\gamma^2-1}, \qquad Q_D = \frac{4\pi e^4 N_m Z\Lambda}{mc^2},$$

Λ—Bethe's logarithm, ν_μ is angle frequency scattering parameter

$$\nu_\mu = F_D\frac{\xi}{4\gamma p}, \qquad \xi = \sum_{i=1}\frac{n_i Z_i^2}{2Z},$$

where ξ—effective charge of molecules, Z_i—the charge of every moleculae component: $Z = \sum n_i Z_i$, n_i—fraction of molecules with nuclear charge Z_i in air, N_m—number density of molecules.

The term Q_{EAS} is the source of secondary electrons generated by EAS and term S_I is ionization integral [11]. Concrete form of Q_{EAS} and S_I will be presented later.

Electric field is increasing inside thunderstorm cloud up to maximum value E_m and then decreasing. In our calculations we choose it in a parabolic form:

$$E(z) = E_m\left(1 - \frac{(z-z_0)^2}{L^2}\right), \qquad -L < z - z_0 < L. \tag{2}$$

Here L is a scale of thundercloud electric field in the height z direction, z_0—corresponds to the centrum of thundercloud.

According to the theory of runaway breakdown one can use the angle averaged equation for the distribution function [7]. Integrating (1) over pitch angles $d\mu$ we find a kinetic equation for distribution function $f(t, \gamma, z)$ of relativistic electrons in the form

$$\frac{\partial f}{\partial t} + c\sqrt{1-\frac{1}{\gamma^2}}\frac{\partial f}{\partial z} = \frac{1}{mc\gamma^2\sqrt{1-\frac{1}{\gamma^2}}}\frac{\partial}{\partial \gamma}\left\{(\gamma^2-1)\left[F_D(\gamma) - eE(z)\right]f\right\} + \frac{S_i}{\gamma^2\sqrt{1-\frac{1}{\gamma^2}}} + Q_{\mathrm{EAS}}(\gamma), \tag{3}$$

where γ is the Lorenz factor.

Ionization integral according to [2,7] is determined by formulae:

$$S_i = \frac{Q_D}{\Lambda mc}\int\limits_{\gamma}^{\infty} y^2 f(t,y,z)\left[\frac{1}{(\gamma-1)^2}+\frac{1}{y^2}\right]dy. \tag{4}$$

To consider source term Q_{EAS} let us take into account that the EAS has a "pancake" form its width in z direction is small enough in comparison EAS radius [8]. It allows to choose the source function Q_{EAS} in a form:

$$Q_{\mathrm{EAS}} = \frac{F_0(\gamma)}{\gamma\sqrt{\gamma^2-1}}\delta(z-ct)\delta(\mathbf{r}_\perp). \tag{5}$$

Supposing EAS pancake form is not changed by the electric field we can neglect small deviations of relativistic velocities from c of secondary electrons $v = c\sqrt{1-1/\gamma^2}$ and search the solution of (3) in the form

$$f(t,\gamma,z) = g(\gamma,z)\,\delta(z-ct)\delta(\mathbf{r}_\perp),$$
$$\gamma\sqrt{\gamma^2-1}\frac{\partial g}{\partial z} = \frac{1}{mc^2}\frac{\partial}{\partial\gamma}\big\{(\gamma^2-1)\big[F_D(\gamma)-eE(z)\big]g\big\} + S_i(g) + F_0(\gamma). \tag{6}$$

Here the distribution function $g(\gamma,z)$ is normalized on total number of electrons N:

$$N = \int\limits_1^{\infty}\gamma\sqrt{1-\gamma^2}\,g(\gamma,z)\,d\gamma.$$

The source term of secondary cosmic rays generated by EAS could be found by comparison with [8]. It has the form:

$$F_0(\gamma) = \frac{\epsilon_p Q_D}{2.29(mc^2)^2}\left\{1 - e^{\varepsilon_1}(1+\varepsilon_1)\int\limits_{\varepsilon_1}^{\infty}\frac{e^{-\lambda}}{\lambda}d\lambda\right\}.$$

Here ϵ_p is the energy of primary EAS particle (in MeV), and $\varepsilon_1 = 1.6\times 10^{-2}\gamma$. We note, that in the absence of electric field E the stationary solution of Eq. (6) describes the cosmic shower equilibrium spectrum in low energy range.

Directly this solution was used as a boundary condition at $z = 10$ of Eq. (6). Note that at $z \geqslant 30$ where electric field disappears the solution comes to the initial equilibrium spectrum automatically.

The solution of Eq. (6) in the disturbed region is shown in Fig. 1. The number of relativistic electrons

$$N = \int\limits_{\gamma_1}^{\gamma_2}\gamma\sqrt{\gamma^2-1}\,g(\gamma,z)\,d\gamma$$

is presented in different energy intervals $[\gamma_1,\gamma_2]$ indicated in Fig. 1 capture. One can see, that the number of secondary EAS electrons in runaway breakdown (RB) conditions increase substantially in the region of existence of electric field $10 < z/l_a < 30$. The increase is growing very rapidly with electric field $\delta = E_m/E_c$ and its maximum shifts towards high values of z/l_a. At high values of $\delta \sim 1.6$–2.0 the increase becomes extremely strong (see Fig. 1(b), (c)). The growth of the full energy W dissipated by runaway electrons in RB-EAS discharge is shown in the Table 1 for $L = 10l_a$. Energy W in the table is expressed in the units of full energy of EAS secondary electrons W_0 in non-disturbed by electric field conditions.

$$W = \frac{e}{mcW_0}\int\limits_{-L/c}^{L/c}E(t)\,dt\int\limits_1^{\infty}(\gamma^2-1)g(\gamma,t)\,d\gamma, \qquad W_0 = \int\limits_1^{\infty}\gamma\sqrt{\gamma^2-1}(\gamma-1)F_0(\gamma)\,d\gamma.$$

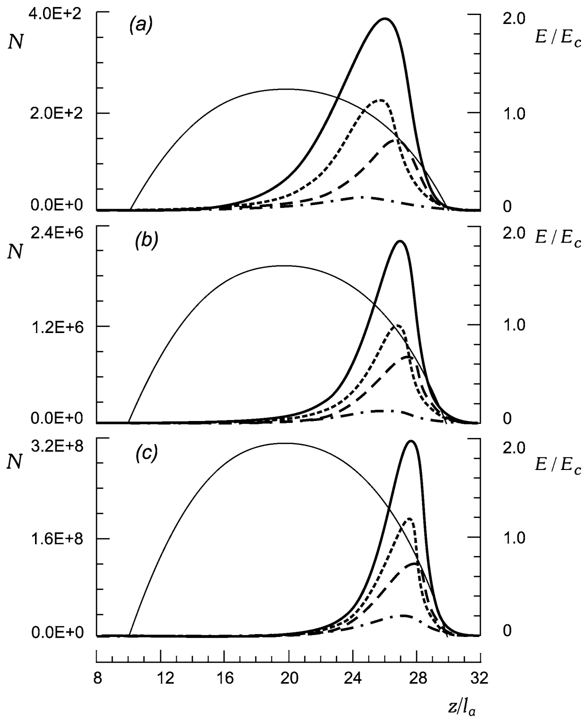

Fig. 1. The dependence of number of relativistic electrons on z/l_a presented for different parameters $\delta = E_m/E_c$ (a) $\delta = 1.2$, (b) $\delta = 1.6$, (c) $\delta = 2.0$. Thundercloud centrum is chosen at $z_0 = 20l_a$. Thin line shows the electric field, dashed line—number of relativistic electrons in energy interval $1 < \gamma < 3$, point line—number of relativistic electrons in energy interval $3 < \gamma < 10$, dashed-point line—number of relativistic electrons in energy interval $10 < \gamma < 100$, solid line—total number of relativistic electrons.

Table 1
The work of electric field

δ	Energy W
1.05	61.5
1.1	122.5
1.2	576.6
1.3	4510
1.4	16844
1.5	2.83×10^5
1.6	2.5×10^6
1.7	1.25×10^7
1.8	4.54×10^7
1.9	1.32×10^8
2.0	3.32×10^8

It means that 1 unit W_0 is approximately 0.1–0.15 of cosmic ray particle energy ε_p generating EAS [8,9]. Thus we see, that even at low values of electric field $\delta = 1.05$–1.20 the dissipated energy exceeds in 6–100 times the energy ε_p of cosmic ray particle generating RB-EAS discharge. At higher values $\delta = 1.4$–1.6 the dissipated energy exceed ε_p at 10^3–10^5 times and at $\delta = 1.8$–2.0 it takes enormous values.

3. Gamma emission

High energy electrons passing through the neutral gas generate X-rays due to bremsstrahlung process. The bremsstrahlung intensity and spectra is determined by electron distribution function $f(\varepsilon, z, t)$:

$$J_\nu = N_m \int \sigma_\nu(\varepsilon) v f(t, \varepsilon, z)\, d\varepsilon = \sigma_b N_m c j_\nu, \tag{7}$$

where v is the velocity of electrons, $\sigma_\nu(\varepsilon)$ the cross-section of the production of photons in the frequency range $d\nu$ by incident electron of energy ε and $\sigma_b = \frac{16}{3} Z^2 \alpha a_0^2$, $a_0 = e^2/mc^2$. Using expression for cross-section [10,11], one can find flux of photons j_ν:

$$j_\nu = \frac{1}{\nu}\int_1^\infty \gamma^2 \ln\left\{\frac{\sqrt{\gamma^2-1}+\sqrt{\gamma^2-1-2\nu\gamma^2}}{\sqrt{\gamma^2-1}-\sqrt{\gamma^2-1-2\nu\gamma^2}}\right\} g(\gamma, z)\delta(z-ct)\delta(\mathbf{r}_\perp)\, d\gamma, \qquad \nu = \frac{\varepsilon_\nu}{mc^2},$$
$$j_\nu = J_\nu^0 \delta(z-ct)\delta(\mathbf{r}_\perp). \tag{8}$$

The expression (7) describes the source of bremsstrahlung photons at given point z and time t. The bremsstrahlung photons propagating through the neutral gas loose their energy due to Compton effect and disappear due to photoionization. The kinetic equation for photon distribution function $I(\nu, z, r_\perp, t)$, describing these processes at $\nu \leqslant 1$ could be presented in a form:

$$-\frac{\partial I}{\partial t} + \frac{c l_T}{3}\Delta I + \frac{c}{l_T}\frac{\partial}{\partial \nu}(\nu^2 I) - c\sigma_{\mathrm{ph}} N_e I + J_\nu^0 \delta(z-ct)\delta(\mathbf{r}_\perp) = 0. \tag{9}$$

Here $l_T = 1/N_e\sigma_T$ is Thompson scattering length, and σ_{ph}—photoionization cross-section.

The solution of diffusion Eq. (9) with the source (7), (8) is

$$I(\nu, z, r_\perp, t) = I_0\left(\frac{2}{3}\pi D\right)^{-3/2}\int_\nu^\infty \frac{d\nu_0}{\nu^2}\sqrt{\left(\frac{\nu_0\nu}{\nu_0-\nu}\right)^3}\exp\left[-\frac{3\nu_0\nu r_\perp^2}{4l_T^2(\nu_0-\nu)}\right]$$
$$\times \exp\left\{-\left[\frac{3\nu_0\nu(z-ct+l_T(\frac{1}{\nu}-\frac{1}{\nu_0}))^2}{4l_T^2(\nu_0-\nu)} + \frac{2\sigma_0}{9\sigma_T}\left(\nu^{-9/2}-\nu_0^{-9/2}\right)\right]\right\} J_{\nu_0}^0\left(ct - l_T\left(\frac{1}{\nu}-\frac{1}{\nu_0}\right)\right). \tag{10}$$

Here normalized photon density

$$I_0 = \frac{\sigma_b N_m}{l_T^2}$$

and we take into account that for a considered energy range $\varepsilon_\nu > 20$ keV the photoionization cross section could be chosen in a form [12]:

$$\sigma_{\mathrm{ph}} = 2^8\frac{\pi}{3}\alpha a_0^2 Z^5\left(\frac{\varepsilon_0}{mc^2}\right)^{7/2}\nu^{-7/2} = \sigma_0\nu^{-7/2}.$$

Here as usually $\alpha = e^2/\hbar c = 1/137$ and $a_0 = e^2/mc^2$.

The solution (10) is shown in Figs. 2–5. At Figs. 2–4 the spectrum of X-ray emission $I(\nu)$ for various values $\delta = E_m/E_c$ is presented. One can see, that the spectrum has very stable form, practically not depending on position z. It always has the distinct maximum at the energies $\varepsilon_\nu \approx 50$–$60$ keV (Fig. 3) and rapidly falls down both to the smaller (due to photoionization) and higher (due to Compton losses) values of ε_ν (identically to [7]). From the Figs. 2, 4 it is seen that the maximal intensity $I_{\max}$ of emission is growing exponentially with electric field E_m. The position of emission maximum $z_{\max}$ is moving slowly in the direction of electron motion.

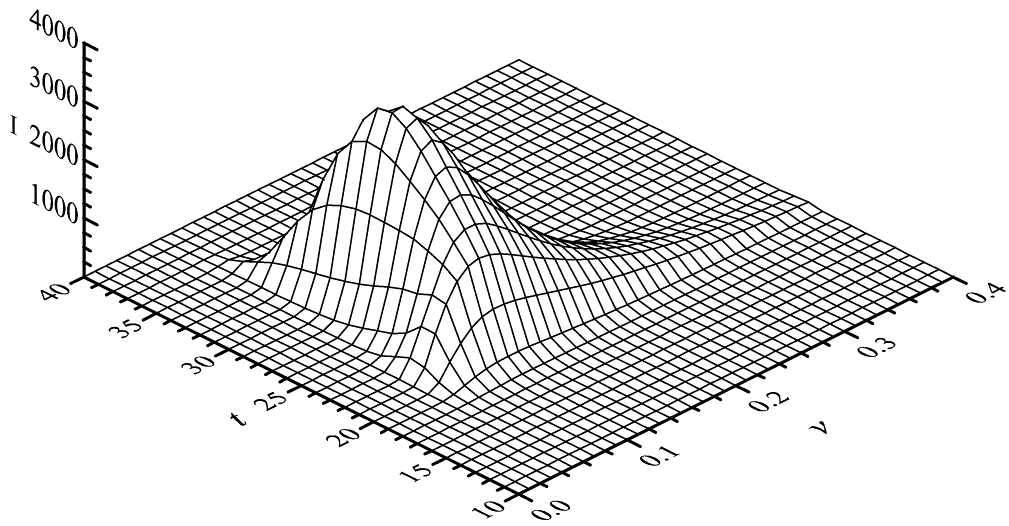

Fig. 2. The dependence of gamma emission intensity I on t and $\nu = \varepsilon/mc^2$ for fixed value $z = 20$ and $\delta = 1.2$.

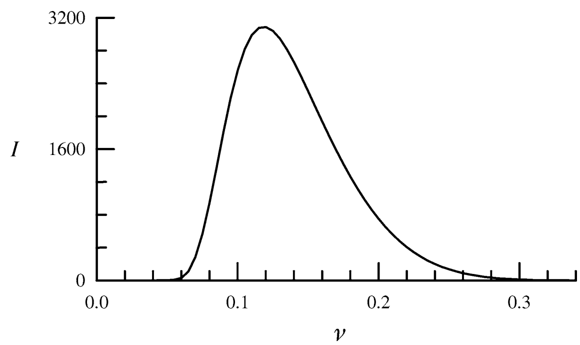

Fig. 3. The dependence of gamma emission intensity I on ν for $\delta = 1.2$, $t = 25$ and $z = 20$.

In the Fig. 5 the propagation of gamma burst generated by of RB-EAS effect is presented. One can see that main gamma signal is accompanying the cosmic ray particle, but a long tail of gamma quanta determined by gamma quanta diffusion is appeared.

Thus we see that in thunderstorm RB conditions both relativistic electrons and gamma spectra of EAS are drastically changed.

4. Main features of RB-EAS discharge

Conventional electric discharge in air take place when the value of electric field exceeds the threshold electric field $E_{\text{th}} \approx 20\ \text{kV/cm}$. Electrons in *conventional discharge* lose their energy mostly to the optic emission and excitation of nitrogen N_2 vibrational levels. Only the tail of the distribution function works to ionization. Thus the main part of the conventional discharge energy goes to optic emission and only a small part to ionization.

In RB-EAS discharge the critical electric field E_c is ten times smaller the conventional threshold breakdown field $E_c \approx 0.1 E_{\text{th}}$. Not very energetic electrons cannot get enough energy from this field to overcome the losses

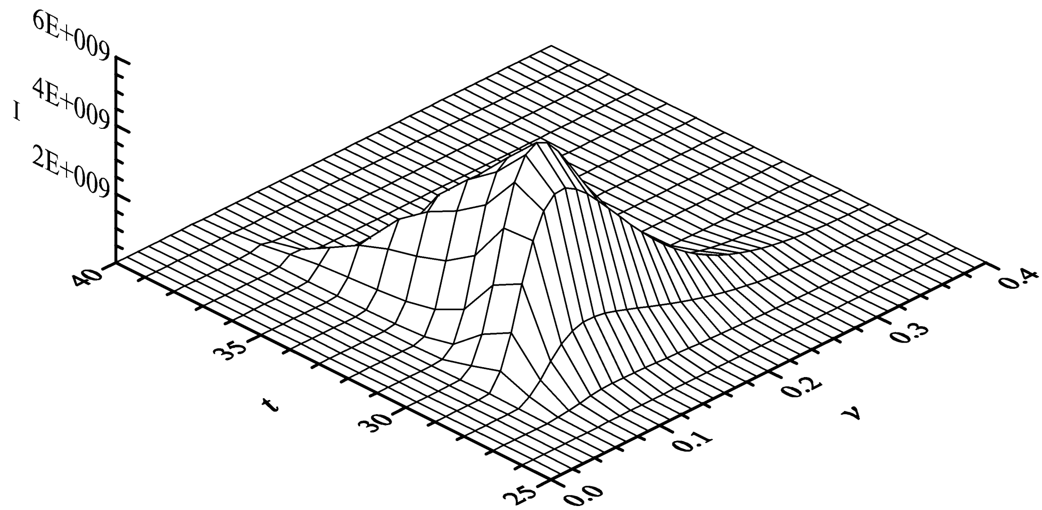

Fig. 4. The dependence of gamma emission intensity I on t and ν for fixed value $z = 30$ and $\delta = 2$.

in collisions with air molecules. Only for relativistic runaway electrons the collisions become rare enough. These electron gaining the significant energy from the electric field could be accelerated.

The energy flux in RB conditions flows from very energetic (relativistic) to low energy (thermal) electrons. The flux loses its energy mostly in ionization process. We remind also, that RB process is stimulated by the seed high energy electrons from external source. In our case this source is secondary EAS electrons generated by a high energy cosmic ray particle when it passes through thundercloud electric field. Exactly these two features: energy flux is going from high to low energy electrons and existence an external source of seed electrons determines the specific features of RB-EAS discharge.

(1) RB-EAS discharge is a one pulse discharge. It takes place when maximal electric field in thundercloud E_m is higher than E_c. Its intensity is growing exponentially with E_m/E_c;

(2) Runaway breakdown is stimulated by cosmic ray secondaries. Their number n_s is proportional to the energy of cosmic ray particle ε_p which generates EAS. Due to this the intensity of RB-EAS discharge is proportional to ε_p;

(3) RB-EAS discharge is generated by thundercloud electric field $\mathbf{E}$. The role of the angle between $\mathbf{E}$ and cosmic ray particle trajectory $\mathbf{R}$ is significant but not decisive. This fact follows from the results of calculations presented at Fig. 1 and Table 1. One can see from the figure that the main part of a newborn electrons has relatively low energies ($\varepsilon < 2$–3 MeV). The electron distribution function as follows from the RB theory [7] is not highly asymmetric at this energy range. In the same time from Table 1 follows that the number of fast electrons is growing exponentially with the value of electric field and parameter L/l_a. Thus with exponential accuracy the dominant role is played by the factors $\delta = E_m/E_c$, L/l_a and ε_p. Note that the role of the angle between $\mathbf{E}$ and $\mathbf{R}$ is growing with the height z;

(4) Energy dissipated in discharge goes mainly to ionization of air molecules (what means production of a large number of low energy thermal electrons) and partly to gamma emission and excitation of forbidden N_2 vibrational levels [14];

(5) Optic emission of RB-EAS discharge is very low (an order of 1% of dissipated energy [13,14]);

(6) Thermal-electron number growth curve is very close to the high-energy one presented at Fig. 1 due to the very small ionization time ($\Delta t_i \sim 10^{-11}$ s). The decay of the thermal electrons number is determined by their attachment to the O_2 moleculas in triple collisions [14];

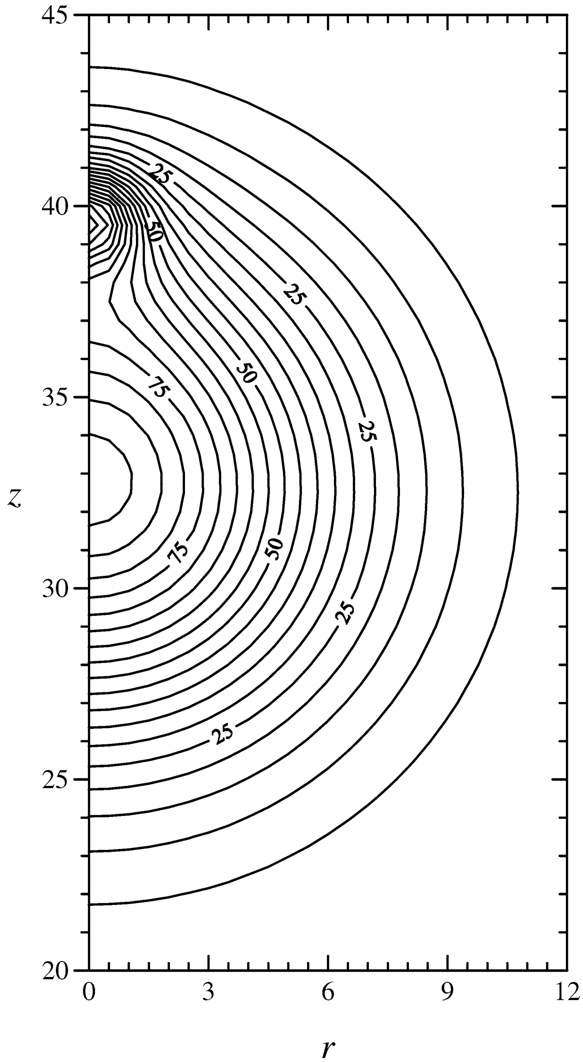

Fig. 5. The dependence of maximum value of gamma emission on z and r for given $t = 40$ and $\delta = 2$: $I(\nu_{\max}, z, r, t = 40) = C_0$; Values $C_0 = 25$, 50, 75 are shown in the figure. The second maximum on distribution is the remnant of huge gamma burst in thundercloud.

(7) Ohmic current of discharge is determined by the motion of newborn thermal electrons during their lifetime in thundercloud electric field [4,14]. (The full number of thermal electrons n_{th} generated in RB-EAS discharge is directly proportional to the work of electric field $n_{\text{th}} \propto W/q$, $q \approx 20$ eV (Table 1).)
Current has a form of unipolar pulse. Current rise time t_r determined by RB process (see Fig. 1). It is inverse proportional to the density of the air molecules:

$$t_r \propto \frac{1}{N_m} \propto e^{z/H}. \tag{11}$$

Current decay time is determined by thermal electrons attachment in triple collisions and thus is proportional to the square density of air molecules

$$t_d \propto \frac{1}{N_m^2} \propto e^{2z/H}. \tag{12}$$

Due to this characteristic time scales of discharge and pulse duration $t_w = t_r + t_d$ are growing with height z in atmosphere from $t_w \approx 0.5$–1 μs at $z \approx 4$–6 km up to $t_w \approx 2$–8 μs at $z \approx 15$–20 km.

(8) Additional current is determined by the flux of relativistic runaway electrons. It generates directed Cherenkov pulse of radio emission [13].

4.1. Radio emission

(1) RB-EAS discharge generates main bipolar radio pulse;

(2) Main radio pulse is generated by the current of thermal electrons. In the ground measurements the electric field of radio pulse could be directed only towards the earth or vice versa. One call it "positive" or "negative" [15,16];

(3) The current pulse intensity J_m is proportional to ε_p. It is growing exponentially with E_m/E_c (at $E_m/E_c > 1$) and with L/l_a. Here L is effective width of electric field region (2);

(4) The power of RB-EAS radio pulse is growing proportionally to J_m^2, where J_m is current pulse maximum. That can lead to extreme values of RB-EAS discharge emission: its power can reach hundreds GW for very high energy cosmic ray particles $\varepsilon_p \sim 10^{18}$–$10^{19}$ eV.

4.2. Electromagnetic cascade discharge

We studied previously the discharge development due to runaway breakdown only. Let us discuss now briefly the role of the whole complex of electromagnetic cascade processes.

Electromagnetic cascade is determined by ionization and mutual transformation of electrons positrons and gamma quanta due to their interaction with air molecules. The main processes at relativistic energies are: ionization, bremsstrahlung, e^+e^- production and Compton scattering. The basic characteristic of electromagnetic cascade is radiation length t_0. The radiation length value in air is $t_0 = 37.1$ g/cm^2. Its equivalent length l_0 in meters at different atmospheric heights is presented in Table 2.

Radiation length is the mean distance over which relativistic electron loses its energy by bremsstrahlung $\varepsilon \propto \exp(-t/t_0) \propto \exp(-s/l_0)$. The pair production by a high energy photons has the mean free path $l_p = 9l_0/7$. Compton scattering mean free path $l_c \approx 0.5 l_0 \varepsilon_{\text{ph}}$, ($\varepsilon_{\text{ph}}$ in MeV). The length l_c is growing effectively with ε_{ph} and due to this Compton scattering is significant for low energy photons only.

RB avalanche length could be presented in a form $l_a \approx 0.17\,(E_c/E)^{3/2}\, l_0$. Thus we see, that in a high enough electric fields $E > E_c$ RB is a dominant process in the whole electromagnetic cascade complex. In the same time in the presence of electric field $E > E_c$ the ionization losses are damped and the cascade changes are very strong:

(1) Every newborn electron in Compton scattering or in pair production became runaway and take part in runaway breakdown. The possibility of RB process amplification was indicated by Dwyer [17];

(2) Spatial spreading of discharge take place. The spreading is determined by the scattering of electrons due to RB and other processes (Compton effect, pair production). Even more effective is the space diffusion determined by gamma quanta. Taking into account the mean free path of Compton scattering one can find gamma diffusion coefficient $D_\gamma \approx 0.5 c l_0 \varepsilon_{\text{ph}}$. Thus the bulk of gamma quanta in energy range $\varepsilon \sim 1$–3 MeV determines the Compton

Table 2
Radiation length in air

z km	0	4	6	8	10	13	15
l_0	300	450	560	700	900	1400	1900

diffusive spreading of discharge

$$R_s \sim \sqrt{c l_0 \Delta t}. \tag{13}$$

For example, at the height 4 km the spreading of discharge from its axes during $\Delta t = 30$ μs is $R_s \approx 2$ km;

(3) Positrons are accelerating in opposite to RB electrons direction. The positrons produce a runaway positron flux. The last process leads to RB amplification;

(4) Due to strong amplification of EAS pair production by RB, the number of low energy positrons will grow up effectively. It should lead to the strong amplification of e^+e^- annihilation line 511 KeV;

(5) The remnants of RB-EAS due to cascade diffusive process could be seen at the significant distance R_s from discharge main axes (13).

Thus we see that the electromagnetic cascade processes lead to amplification of RB effect, spreading of RB-EAS discharge and strong growth of positron flux.

5. Discussion

Let us compare RB-EAS discharge theory with the results of recent observations.

5.1. Mountain experiments

(1) Experiments devoted to direct observations of RB-EAS discharge were fulfilled at Tien Shan Mountain Scientific Station (height 3300–3500 m) [18]. A special trigger antenna array was constructed on the basis of SIG 5 counters. Antenna was wide spread (~ 0.1 km^2) and allowed to fix pulses of gamma emission from EAS generated by cosmic ray particles having energy $\varepsilon_p \geqslant 2 \times 10^{14}$–$10^{15}$ eV. Average time interval between EAS observed by antenna was 2.5 s;

(2) Signal from EAS antenna were used for triggering of radio installation. During two thunderstorms there were observed 150 simultaneous gamma and radio pulses. Note that in quiet (non thunderstorm) time radio pulses were absent;

(3) The observed radio pulses were coming from thunderstorm mainly close to horizon direction. They had a bipolar form with full width ~ 0.5–0.7 μs. The maximum of electric current pulses generating radio pulses was determined to be a few amperes $I_m \approx 1$–5 A. Comparison of radio observations with the prediction of RB-EAS theory [18] demonstrate a good agreement. Supposed value of maximal electric field in the thundercloud $E_m/E_p \approx 1.2$–1.4;

(4) The gamma emission observed by triggering antenna came with time delay. This time delay is due to the diffusion of gamma quanta between RB-EAS region in thundercloud and trigger antenna. The time delay of gamma emission ~ 10–100 μs is in agreement with the electromagnetic cascade theory (11);

(5) One can conclude: the results of Tien Shan experiment are in reasonable agreement with the theory of RB-EAS discharge in thunderclouds at the low heights (4–6 km) for the low energy cosmic ray particle $\varepsilon_p \sim 10^{15}$ eV. The value $E_m/E_p \sim 1.2$–1.4 are needed to obtain the observed radio and gamma fluxes.

5.2. Lightning leader initiation

(1) It is well known that the maximal values of electric field measured at thunderclouds are significantly lower than the field needed to excite the classical streamer discharge [32]. On the other hand these values are close to the critical field for runaway breakdown E_c [5,19] and may be 1.2–1.5 times higher than E_c [20–22]. Note that RB-EAS discharge is a very short time process (~ 1 μs) in comparison with lightning. That is why it seems quite natural to study the possibility of lightning initiation by RB-EAS discharge;

(2) To investigate lightning initiation process purely radio observations were performed. The initial radio emission of lightning was studied using high time resolution wide band interferometer [23]. The result of all our radio observations was the following: lightning initiation process is always characterized by isolated bipolar radio pulse. Pulse could have negative or positive polarity. Pulse width for low altitude cloud to ground lightning (4–6 km) is about 0.5–0.7 μs. Pulse field amplitude is of the order of (50–1000) mV/m, distance to the source (10–100) km. It corresponds to electric current pulse (0.1–1) kA;

(3) The current is generated by thermal electrons moving in thundercloud electric field. The velocity of thermal electrons is low $\sim 10^6$ cm/s. To produce the observed radio pulse the density of free electrons generated by "ionizator" should grow up very rapidly. The analysis of the observational data demonstrate that the ionizator speed is close to velocity of light. The RB process stimulated by high energy cosmic ray particle could serve as such ionizator;

(4) The theory presented here demonstrate that the ionizator and the radio pulse could be generated in thundercloud by RB-EAS discharge. Thus the RB-EAS discharge could serve for lightning initiation process. Observed values of pulse maximal current could be reached if the energy of cosmic ray particle $\varepsilon_p \geqslant 10^{16}$–$10^{17}$ eV and maximal thunderstorm electric field take values $E_m/E_p \approx 1.2$–1.5. Preliminary analysis of lightning statistics (see [24,25]) shows that the flux of cosmic ray particles with $\varepsilon_p > 10^{16}$ eV is sufficient to serve for lightning initiation [23];

(5) After the first initial pulse a chain of short pulses is seen. The time between pulses ~ 10 μs. The current in all pulses has the same direction as the first one. The full process of development of lightning step-leader needs further investigation. The lightning leader problem is discussed widely in the literature [5,19].

Note, that lightning leader is initiated by medium current pulses $J \sim 0.1$–10 kA. Very low pulse is insufficient to initiate the process and the very strong one served itself as the fast preliminary discharge.

5.3. Narrow bipolar pulses

Narrow bipolar pulses are short time isolated discharges [26,28]. Their main features:

(1) NBP are high altitude discharges. Their main location [16]
$z = 15$–20 km for NNBP (sharp peak near 18 km)
$z = 7$–15 km for PNBP (sharp peak near 13 km);

(2) Time characteristics of NBP [26,27]
mean rise time ~ 1–2 μs,
full width at half maximum $\sim (2$–$5)$ μs,
full rise + fall time $\sim (5$–$10)$ μs;

(3) NBP is observed as low frequency 0.2–0.5 MHz bipolar ground electromagnetic wave with large amplitude. The NBP effective field amplitude was measured simultaneously at several stations situated at different distances R [16,27]. Characteristic wave field is

$$E \sim (10\text{–}30)\left(\frac{100\ \text{km}}{R}\right)\text{V/m};$$

(4) Electric current pulse, generating NBP is unipolar and its maximum reaches values

$$J_m \sim (30\text{–}100)\ \text{kA}$$

Electric current is generated by thermal electrons;

(5) From the analysis of observational data it follows that the NBP current initiator (or "ionizator") moves with very high speed. The speed of initiator is determined as 7.3×10^9–3.0×10^{10} cm/s [26] or $\sim 10^{10}$ cm/s [28].

Let us compare NBP with the theory of RB-EAS discharge generated at high heights 13–18 km by very energetic cosmic ray particles ($\varepsilon_p \geqslant 10^{17}$–$10^{19}$ eV). Characteristic time parameters of RB-EAS discharge at high heights are given by formulas (11), (12). One can see that both growth and relaxation time characteristics roughly agree with NBP observations. Electric current is unipolar. As follows from Table 1 for $E_m/E_c \approx 1.4$–1.5 and $\varepsilon_p \approx 10^{17}$–$10^{19}$ eV currents main peak reaches the values which generally are in agreement with the available data of NBP observations presented by Smith et al. [16,26,27].

5.4. Gamma emission

One of the main characteristics of RB-EAS discharge is powerful pulse of gamma emission. Pulse time scale is 1–10 µs. Pulse intensity is falling down with distance r from the source due to attenuation and spreading. Attenuation determined by radiation length plays the main role for observation of gamma rays in lightning initiation process. For gamma emission at NBP heights the rapid growth of radiation length with height in atmosphere allows to neglect attenuation at $z > 20$–25 km. It gives an opportunity to observe gamma pulse from satellites. As is well-known gamma emission from the earth was already observed at satellite BATSE [29,30]. But the source of this emission remains unknown yet.

The simultaneous observations of radio and gamma pulses can give quite definite indication of the RB-EAS discharge realization.

5.5. Coherence effect

It should be especially singled out the *coherence on NBP low frequencies (LF) radio emission process*. The pulse current region determined by the EAS scale is $l_a \sim 300$–400 m. For LF radio emission (200–500) kHz the scale L_c is of the order or less than the length of radio wave $\lambda = (600$–$1000)$ m. It means that the LF radio emission is coherent process and due to this the *power of radio emission in LF is growing with current J proportionally to J^2*. That is why the ground wave power in NBP could reach extreme values:

$$P = \frac{2J^2}{3c}, \quad P \approx (100\text{–}300)\ \text{GW}.$$

It means that emitted by radio pulse energy can reach 0.2–1 MJ. We see that the work of thunderstorm electric field in NBP is really *giant*: it exceeds 10^6 times the energy of cosmic ray particle triggering the process.

Note that in lightning initiation process the radio emission is *coherent* as well. But the current J_m and thus the power of emission proportional to J_m^2 is much less. For $J_m \approx 0.1$–1 kA the energy of radio emission is compatible with the energy dissipated on ionization and generation of thermal electrons during RB-EAS discharge.

One can see the following chain of measurements which show the rough proportionality between J_m and ε_p:

Tien Shan experiment

$$\varepsilon_p \sim 10^{15}\ \text{eV}, \qquad J_m \sim 1 - 10\ \text{A}.$$

Lightning first pulse measurements

$$\varepsilon_p \sim 10^{16}\text{–}10^{17}\ \text{eV}, \qquad J_m \sim 0.1\text{–}1\ \text{kA}$$

NBP

$$\varepsilon_p \sim 10^{17}\text{–}10^{19}\ \text{eV}, \qquad J_m \sim 10\text{–}100\ \text{kA}.$$

Thus RB-EAS discharge can serve as background for explanation of observed phenomena.

Note that the high values of maximal electric field $E_m/E_c \approx 1.2$–1.5 were supposed in our estimates. The direct observations of electric fields both at low and high heights gave usually lower values yet [20,31]. Though at 4–6 km the data which show values $E/E_c \approx 1.3$–1.5 exist [21,22]. Note that NBP are usually seen in the active phase of storm near reflectivity core with 50 dBz radar reflectivity [26]. According to [16] the strong positively charged layer at the heights (15–16) km exist between generation maximum of NNBP and PNBP.

6. Conclusion

The following main statements could be formulated in conclusion:

(1) The RB-EAS discharge theory is developed;

(2) The comparison with existing observational data show the reasonable agreement. The RB-EAS discharge do exists in thunderstorm atmosphere;

(3) The simultaneous observations of radio and gamma pulse emission could serve for direct indication of RB-EAS discharge;

(4) Extremely strong growth of radio pulse power with cosmic ray particle energy is predicted. This radio pulse could be easily observed at giant distances (up to 1000 km). We suppose it is just seen as NBP;

(5) The detailed studies of this phenomena could lead to development a new methods of *RB detection of a very high energy cosmic ray particles* $\varepsilon \geqslant 10^{18}$ eV;

(6) The theory predicts extremely strong pulses of gamma emission accompanying NBP events. This effect should be carefully studied experimentally, as it take place around the plane flight height region about 10 km and higher. For measurements of NBP gamma pulses generated at heights 15–20 km it is convenient to use satellites.

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