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SOURCE OF RUNAWAY ELECTRONS IN THUNDERCLOUD FIELD STIPULATED BY COSMIC RAY SHOWERS

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Introduction

Lightning discharge initiation remains intriguing unsolved problem in the physics of atmospheric electricity. The possibility of initiating thunderstorm discharges by cosmic radiation has been repeatedly analyzed. In 1924 Wilson justified an idea that relatively weak thunderstorm electric fields are capable to accelerate electrons. The idea was confirmed by detection of significant increases of penetrating radiation during thunderstorms (cf. [1-4] and citations therein) and hard gamma-ray flashes detected aboard satellites [5, 6]. A mechanism of electric breakdown in the atmosphere combining the cosmic-ray effects and relativistic runaway electron (RE) avalanches was proposed [7] and developed (cf. [8-12] and references therein). To numerically simulate the breakdown within the scope of this mechanism, it is necessary to know a source of seed REs produced by cosmic rays in the atmosphere. The aim of this paper is to present the calculated RE source as a function of the altitude h above the Earth's surface and the field overvoltage $\delta = eE/(F_{\min} \cdot P)$ relative to the minimum $F_{\min}$ =218 keV/(m·atm.) of the drag force $F(\varepsilon)$ affecting an electron with energy ε in air as described by the Bethe formula [13]. More details are available elsewhere [14].

Technique of computations

Propagation of cosmic radiation through the atmosphere was simulated using the Monte-Carlo technique based on the idea of a nuclear cascade [15] in the framework of the following simplifications. Since the transverse size of the extensive cosmic-ray shower, 100 m [15], is less than the longitudinal extent along the vertical, 10-20 km, the 1D problem was solved. All secondary particles were assumed to move along the direction of motion of primary protons predominating in the cosmic rays [15]. The energy dependence of the proton flux was approximated as follows:

$$J(1/\mathrm{m}^2 \cdot \mathrm{s} \cdot \mathrm{ster} \cdot \mathrm{GeV}) = \begin{cases} 1000 \cdot \varepsilon^{-1.7}, & 1\,\mathrm{GeV} < \varepsilon < 10\,\mathrm{GeV} \\ 12100 \cdot \varepsilon^{-2.68}, & \varepsilon > 10\,\mathrm{GeV}. \end{cases} \tag{1}$$

A simplified model of the nuclear cascade was adopted [16]. It was assumed that a proton completely loses its energy in the first interaction with air nuclei, producing 15 pions with equal energies.

$$p + N = N + 5\pi^0 + 5\pi^+ + 5\pi^- . \tag{2}$$

The proton range is of 70 g·cm^{-2}. Pions with the range of 100 g·cm^{-2} also produce 15 pions of the next generation. In this reaction, pions spend all their energy or decay:

$$\pi^\pm \to \mu^\pm + \nu_\mu , \quad \pi^0 \to \gamma + \gamma , \\ \hookrightarrow \quad \mu^\pm \to e^\pm + \nu_e + \nu_\mu . \tag{3}$$

Produced photons generate electron-photon cascade through reactions of photoproduction of electron-positron pairs and electron bremsstrahlung.

$$\gamma + N \to N + e^+ + e^- , \quad e^\pm + N \to N + e^\pm + \gamma \tag{4}$$

The range between these interactions is of 37 g·cm^{-2}. Ionization energy losses of electrons and positrons were taken into account using differential approximation. The bremsstrahlung process is ignored if the electron energy ε is lower than the critical ε_{rad} = 80 MeV. In the region of low photon energies, the process of pair production is changed by the Compton effect with the cross section from [17].

$$\gamma + N \to N + \gamma + e^- \tag{5}$$

To simplify the calculations the photon energy was limited from below by 1 MeV, assuming that photons of lower energies are absorbed.

To obtain the source of REs, we calculated a number of secondary electrons with energies above the runaway threshold ε_c depending on the overvoltage δ [18].

The flux of primary radiation was divided into 20 angular groups containing equal number of particles. The isotropy of the primary cosmic radiation was taken into account. The contribution of the particles from group *j* to the linear RE number density at the altitude *h* was calculated as a sum over all species of particles with energy ε_i,

$$S_j = \sum_i \frac{1}{\lambda(h,\varepsilon_c,\varepsilon_i)\cdot\cos\alpha_j} = \sum_i \frac{n(h)\cdot Q(h,\varepsilon_c,\varepsilon_i)}{\cos\alpha_j} , \tag{6}$$

where $\lambda(h)$ is the local particle range until the ionization event, $n(h)$ is the number density of air molecules, Q is the cross section of production of secondary electron with the energy above ε_c, $\cos\alpha_j = 1-(j-1)/20$ is the cosine of the angle between the direction of motion of particles of the group *j* and the vertical. The cross sections were taken from [13].

Formula (6) makes it possible calculating the RE linear number density created by the group *j*. Multiplying the result by the flux density of the primary cosmic radiation in this angular group Φ_j and summing over all groups gives the RE source

$$S_{RE}(\varepsilon_c, h) = \sum_{j=1}^{20} \Phi_j \sum_i \frac{n(h)\cdot Q(h,\varepsilon_c,\varepsilon_i)}{\cos\alpha_j}. \qquad (7)$$

Results

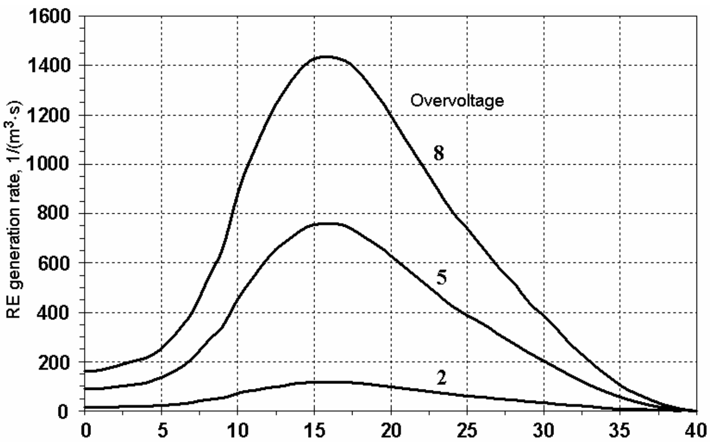

Fig. 1.

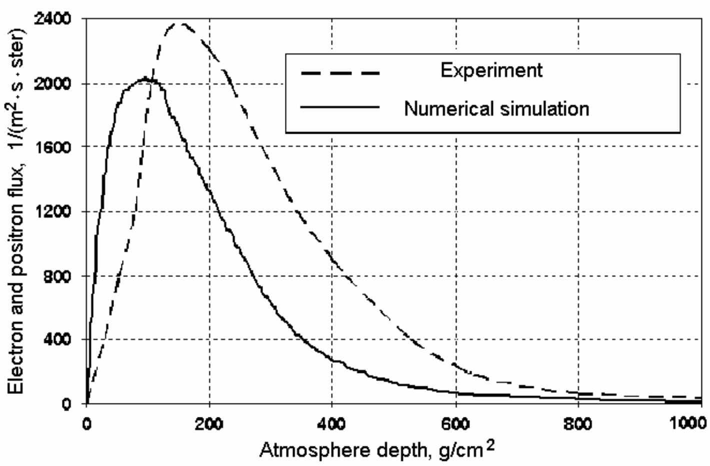

Fig. 2.

It is convenient to present the source as $S_{RE}(\delta) = S_{RE}(\varepsilon_c(\delta))$. The physical sense of $S_{RE}(\delta)$ is the specific generation rate of the secondary electrons by cosmic radiation. The energy of these electrons should be sufficient to continuously accelerate, i.e., to become runaways, in electric field with overvoltage δ. The fig. 1 presents the altitude variation of the RE source calculated for three δ. In view of the lack of the experimental data on the RE source it is impossible to directly estimate the accuracy of the obtained source. However, the RE source was calculated based on the vertical distributions of the secondary radiation components and the particle spectra at different altitudes found in the process of the simulation. Therefore, the reliability of the model was indirectly verified by comparing results of secondary radiation calculations with known experimental altitude variations in the secondary cosmic rays and with the spectra of these rays [19, 20]. In fig. 2 the calculated dependence of the electron and positron flux with energies above 100 MeV is compared to the dependence based on the available experimental data [20]. The agreement is satisfactory.

Conclusions

A source of runaway electrons was calculated as a function of the electric field overvoltage and the altitude above the Earth's surface. It is recommended as a source of relativistic runaway electron avalanches in numerical simulations of electric discharges in atmosphere controlled by REs in thunderstorm fields and their emissions (optical, gamma and neutrons). The source was used to simulate the upward discharge and its emissions [11, 12]. The calculated gamma-ray pulses agree with detected terrestrial gamma-ray flashes [5, 6].

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