The magnetic field generated by a critical avalanche of runaway electrons

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X-ray and gamma flares observed in the Earth's atmosphere during a thunderstorm are associated with the generation of runaway electrons in the atmospheric electric field. It is assumed that the main role in high-altitude discharges observed in a thunderstorm atmosphere is played by avalanches of runaway electrons initiated by cosmic rays. Using numerical calculations, in which the process of electron acceleration under the influence of a constant electrostatic force was simulated, the patterns of the evolution of avalanches of runaway electrons in air are investigated and the parameters of the critical avalanche of runaway electrons are determined.

Introduction

In the last century, in thunderstorm atmospheric discharges [1], x-ray and gamma-ray bursts were detected, the presence of which was associated with the generation of runaway electrons (REs) in electric atmospheric fields. In 1992 [2], the effect was predicted, which was called runaway electron breakdown (REB). It is assumed that it is REB that is realized in high-altitude atmospheric discharges [2–4], which are observed in a thunderstorm atmosphere 10–50 km from Earth level. The main role in the evolution of REB is played by avalanches of runaway electrons initiated by cosmic rays [3]. REB is characterized by a low electric field strength at which this type of breakdown develops. The possibility of the existence of REB is also associated with increased interest in the study of runaway electron generation under laboratory conditions, both theoretical [4–7] and experimental [8, 9].

The appearance of runaway electrons in a substance located in an electric field with intensity E is is associated with a decrease in the braking force [10]. This force is associated with inelastic losses, with increasing electron energy. The braking force has a maximum and a minimum. Moreover, the maximum lies in the region of low (nonrelativistic) electron energies, and the minimum in the region of ultrarelativistic energies. The maximum braking force corresponds to the value of the electric field $E_{cr} \approx F_{\max}/e$, where $F_{\max}$ is the maximum value of the braking force, e is the electron charge. The value of the electric field E_{cr} is called critical, since when it is reached, all the electrons in the gas begin to continuously accelerate.

Introduction

The maximum braking force corresponds to the value of the electric field $E_{cr} \approx F_{\max}/e$, where $F_{\max}$ is the maximum value of the braking force, e is the electron charge. The value of the electric field E_{cr} is called critical, since when it is reached, all the electrons in the gas begin to continuously accelerate. However, the fulfillment of condition $E \geq E_{cr}$ is not necessary for the appearance of runaway electrons in the gas. In the range of field intensities $E_{th} < E < E_{cr}$, where $E_{th} \approx F_{\min}/e$ is the threshold electric field strength corresponding to the minimum braking force ($F_{\min}$), in order to switch to the continuous acceleration mode, an electron with a charge e must have some energy reserve. In the atmosphere at sea level, the threshold electric field strength is $E_{th} \approx 2.75$ kV/cm [11].

For the appearance of REB in the Earth's atmosphere, it is necessary to have electric fields with intensity $E > E_{th}$. In this case, when an electron with a kinetic energy $\varepsilon_k > \varepsilon_k^{\min}$ appears, an RE avalanche is formed. The number of electrons in the avalanche increases exponentially $N_{es} = N_0 \cdot \exp\{l/l_a\}$, where N_0 is the initial number of particles, l is the length of the path covered by the avalanche, and l_a is the exponential growth length of the RE avalanche. An increase in the number of REs in the avalanche can lead to the fact that the space charge field becomes comparable with an external electrostatic field. This situation is similar to the so-called avalanche-streamer transition in ordinary electron avalanches [12].

Description of the Model

For modeling RE avalanches, a three-dimensional numerical model based on the Monte-Carlo method was used. The basic equation of the model was the equation describing the momentum, which was solved for each electron:

$$\frac{d\mathbf{p}}{dt} = -e\mathbf{E} - \mathbf{F}\left(\varepsilon_k\right) - \left(\Delta\mathbf{p}\right)_{el} \quad (1)$$

where $\mathbf{p} = m\mathbf{v}\Big/\sqrt{1-v^2/c^2}$ is the electron momentum; **v** is its speed; $(\Delta\mathbf{p})_{el}$ is the change in momentum in elastic collisions with air molecules; $F(\varepsilon_k)$ is the braking force. The technique for modeling avalanche of REs is described in detail in [13–15]. Numerical modeling was carried out for air. During the simulation, the gas pressure and the external electric voltage *E*, which had one component directed along the z axis, were changed. At the initial instant of time (t = 0), at the origin, there was one electron with energy $\varepsilon_k = 10\varepsilon_{kmin}$. After passing through the avalanche of runaway electrons, an ionic “cloud” remains in the gas. The parameters of the ion "cloud" were calculated under the assumption that the ions are motionless. Since the number of electrons in an avalanche can reach 10^{18} particles, the numerical calculation of the parameters of such avalanches requires the use of the procedure for combining or enlarging particles [16].

Description of the Model

The results of numerical calculations of the parameters of critical runaway avalanches of electrons (CREA) according to the model described above are presented in Fig. 1. This figure shows the dependences of the number of electrons in the CREA on the strength of the external electric field at various air pressures. In this figure, the solid lines show the calculated curves, and the dashed lines correspond to the estimate obtained in accordance with the following assumptions. The number of electrons in a critical avalanche can be estimated by comparing the space charge field with an external electrostatic field, that is, from the expression [15]:

$$\frac{eN_{es}^{cr}}{\Delta_{\perp}^{2}} \approx E \qquad (2)$$

where $\Delta_{\perp}$ is the size of the avalanche across the field. Note that $\Delta_{\perp} \approx l_a$ [15]. Expression (2) shows that in determining the number of electrons in a critical RE avalanche, the exponential growth length of the RE avalanche is important.

Simulation Results

In [15, 16], to determine this quantity, it was proposed to use the following expression:

$$l_a \approx \frac{mc^2}{eE} \ln\left(\frac{2mc^2}{J}\right)\left(1-\sqrt{\frac{E}{E_{cr}}}\right) \quad (3)$$

where $E_{cr} \approx (4\pi e^3 Zn)/(2.718J)$ [17], *m, e* is the mass and charge of the electron, *J* is the average energy of inelastic losses in the gas. In air, in which nitrogen is the most representative gas, the value of *J* is 80 eV.

However, expression (3) does not reflect the tendency of the exponential growth length of the RE avalanche to infinity at $E \rightarrow E_{th}$ [11], where $E_{cr} \approx (4\pi e^3 Zn)\cdot(mc^2)^{-1}\cdot\ln(2mc^2/J)$ [15]. Expression (3) can be modified as follows:

$$l_a \approx \frac{mc^2}{e(E-E_{th})} \ln\left(\frac{2mc^2}{J}\right)\left(1-\sqrt{\frac{E}{E_{cr}}}\right) \quad (4)$$

Simulation Results

Expression (4) differs from (3) in that it takes into account the tendency of the exponential growth length of the RE avalanche to infinity at $E \to E_{th}$ [11]. This is a consequence of replacing the factor $(mc^2/eE) \to (mc^2/e(E\text{-}E_{th}))$. Then from (2), taking into account (4), we obtain the following estimate

$$N_{es}^{cr} \approx \chi \frac{m^2 c^4}{e^3} \frac{E}{(E - E_{th})^2} \left[\left(1 - \sqrt{\frac{E}{E_{cr}}} \right) \ln\left(\frac{2mc^2}{J} \right) \right]^2 \qquad (5)$$

where χ is the dimensionless parameter due to the geometry of the avalanche [15] (when constructing the curves in Fig. 1, it was assumed that $\chi = 3$).

Simulation Results

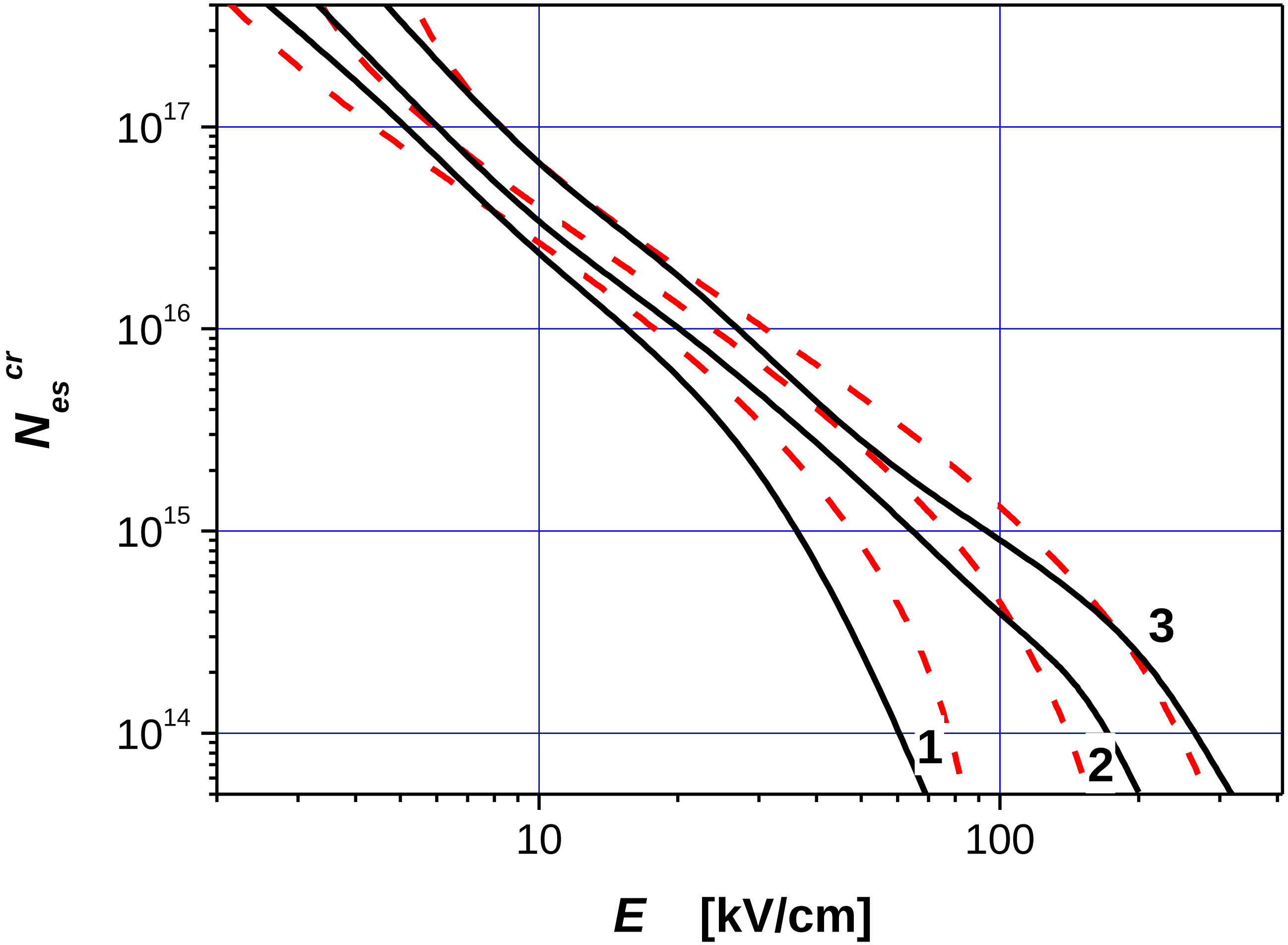

Fig. 1 Dependences of the number of electrons in the CREA on the electric field strength at various air pressures: curves 1 – 0.25 atm; curves 2 – 0.5 atm; curves 3 – 1 atm. Solid lines - numerical calculation, dashed lines - estimates according to (5).

CONCLUSION

As can be seen from Fig. 1, expression (5), based on the modified expression (4), describes quite well the results of numerical calculations in the entire range of possible values of the electric field $E_{th} < E < E_{cr}$. Expressions (4) and (5) allow us to estimate the current of the critical avalanche of REs and the magnitude of the magnetic field that it creates. The amplitude of the current pulse of runaway electrons in a critical avalanche can be estimated as follows:

$$I_{es}^{cr} \approx \frac{v_{\parallel} e N_{es}^{cr}}{2\Delta_{\parallel}} \approx \frac{ceN_{es}^{cr}}{2l_a}$$

where $v_{\parallel}$ and $\Delta_{\parallel}$ are the velocity and size (standard deviation) of the RE avalanche along the electric field. Then the current achieved in critical avalanches of REs propagating under conditions close to those realized in high-altitude atmospheric discharges can be estimated at hundreds of kiloamperes, and the magnetic field induced by such an avalanche can be estimated at tens of Gauss, which is two orders of magnitude higher than the magnetic field of the earth.

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