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Ionisation of air by electron avalanches in a cloud

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Abstract

Electron avalanches developing in electrified clouds are known to be the source of thunderstorm-correlated gamma-radiation. Avalanche development is accompanied by radio-emission similar to that of a lightning and have a strong influence on the air ionisation. The analytical model of electron avalanche in a cloud is developed and applied to consideration of a quasistationary mode of avalanche development, corresponding to gamma-ray glows. The estimated number of gamma photons in an avalanche is of the same order of magnitude as the number of fast (runaway) electrons. The possibility of the increase in conductivity by ten orders of magnitude due to avalanches development in a cloud is shown. Electric curent of avalanches formed in a thundercloud can be comparable with current of lightning discharge. Therefore, the both processes — lightning and electron avalanche — are crucial for understanding electric structure and mechanisms of emission of thunderclouds.

1 Introduction

The most energetic electric phenomena of the lower atmosphere are lightning discharges and energetic particle fluxes developing in clouds. Both processes are very sensitive to the ionization in the cloud. The study of these phenomena provides information on the air ionization, which is not available in direct measurements. The gamma radiation of clouds is a consequence of the acceleration and multiplication of energetic particles in a strong field of 1 km scale, while the initiation and development of lightning is a much more localised process. Thus, the consideration of gamma-emission provides a unique opportunity to estimate the ionization in the vast regions of an electrified cloud. Gamma radiation originating from clouds in Earth's atmosphere could be observed by spacecraft-based and ground-based detectors. Upwards-directed gamma emission of clouds is observed as terrestrial gamma-ray flashes (TGFs) [1]; radiation registered under a thundercloud is called the thunderstorm ground enhancement (TGE) [2]. TGF and TGE produce gamma-radiation with photon energy 1–100 MeV. Energetic radiation of a cloud occurs due to bremsstrahlung of runaway relativistic electron avalahcnes developing in the cloud (RREA, [3]). Runaway is the accelerated motion of an electron in air, whicih is possible in the electric field exceeding $E_{th} = 2.8 \cdot 10^5 \times n$ (n is the air density relative to its value at sea level under normal conditions) [4], [5]. For a runaway electron an energy gain caused by electric field exceeds energy lose caused by interaction with air, mainly ionization and bremsstrahlung processess. E_{th} is close to the maximum value of the electric field measured in the cloud [6]. In what follows a region within the cloud with electric field exceeding E_{th} is called a strong fiels region. Runaway electrons ionize the air, producing secondary electrons, which results in the avalanche multiplication of electrons. Seed particles initiating avalanches have energy more than 0.1–1 MeV and are provided by secondary cosmic rays.

2 Relativistic feedback

The mechanism of relativistic feedback in the runaway electron avalanche process [5] takes into account the possibility of creating of new avalanches by electrons of initial avalanches. The relativistic feedback mechanism makes possible a new complex type of behavior that is different from the RREA process. avalanche. Positrons and energetic quanta of the initial avalanche are capable of moving to the beginning of the strong field region and producing new high-energy electrons, which can generate new avalanches. A positron can produce a free runaway electron scattering on an atomic electron (Bhabha scattering). Positrons are produced by electron-positron decay of photons created in the process of avalanche development. X-rays providing the other type of relativistic feedback can be produced as a result of annihilation or bremsstrahlung emittion. An energetic photon produces a secondary electron which can become runaway as a result of photoelectrical effect or Compton scattering. Thus, the quanta emitted by the initial avalanche do not increase the electron multiplication intensity in this avalanche, but lead to the occurrence of additional avalanches; thereby significantly increasing the quantity of particles at the exit of the strong field region.

In order to estimate an influence of avalanche on ionosation in a cloud, dynamics of concentration of energetic particles should be considered. N_f, N_s, N_p, N_γ, N_n, N_{i+} and N_{i-} are quantities of fast electrons (with a characteristic energy of about 7 MeV), slow electrons (energy from several eV up to 10 keV), positrons, gamma rays, neutral atoms and molecules, positive and negative ions correspondingly. It is known that N_f, $N_s << N_n$; $\frac{N_s}{N_f} = 10^3 \div 10^6$ [7]. An average speed of runaway electrons is almost independent on electric field and equals to $v = 0.89 \cdot c$, where c is the speed of light. Speed of positrons is close to c because positrons do not lose energy in avalanche multiplication process [5]. Speed of slow electrons and ions is much lower.

The proposed analytical model takes into account the processes listed below. Characteristic frequencies for conditions in a strong field region are indicated per one particle.

1. Generation of runaway (fast) and slow electrons by ionisation with frequencies ν_f and ν_s correspondingly. $\nu_s = 10^{12}\ s^{-1}$, the dependence of ν_s on electric field strength is negligible [7], [3].

$$\nu_f = 10^2 \frac{E(\frac{kV}{sm})}{n} s^{-1}. \tag{1}$$

2. Attachments of runaway and slow electrons to neutral molecules, $\nu_{at} = 10^8\ s^{-1}$. Recombination rate is negligible because ion concentration is much lower than neutral atoms and molecules [5].

3. Bremsstrahlung produced by runaway electrons, $\nu_{br} = 10^6\ s^{-1}$. The estimate is based on the values of characteristic length of emission for a runaway electron with energy > 1 MeV (which is $310 \cdot n^{-1}$ m) [5]. W is a probability of electron-positron decay of a photon. Consequently, the rate of slow electron production is $\nu_b r \cdot (1+W)$, the rate of positron production is $\nu_{br} \cdot W = 3 \cdot 10^{-4}$ positrons per 1 m for one runaway electron [5], which leads to $W = 10^{-2}$.

4. Positron annihilation with an atomic electron, $\nu_{an} = 3 \cdot 10^6\ s^{-1}$ per one positron. The rate of positron annihilation with a free electron is negligible [5].

5. Bhabha scattering (electron-positron scattering), ν_{bs} per one positron.

6. Photoelectric effect and Compton effect could be described by integral rate, because both processes cause creation of a runaway electron and a decrease of quantity of energetic photons. The estimate $\nu_c = 5 \cdot 10^4\ s^{-1}$ is obtained with use of Klein–Nishina formula for the Compton scattering of a photon with energy 10 MeV on an atomic electron. The rate of Compton scattering on a free electron is negligible because $N_f, N_s << N_n$.

3 Analytical model of avalanche process

A system of equations is derived describing dynamics of electron avalanche with relativistic feedback processes taken into acccount:

$$\begin{cases} \frac{\partial}{\partial t} N_f = (\nu_f - \nu_{at} - \nu_{br}) N_f + \nu_{bs} N_p + \nu_c N_\gamma - \nu \frac{\partial}{\partial x} N_f \\ \frac{\partial}{\partial t} N_s = (\nu_s + \nu_{br}(1+W)) N_f - \nu_{at} N_s + \nu_{an} W N_p \\ \frac{\partial}{\partial t} N_p = \nu_{br} W N_f - \nu_{an}(1-W) N_p + c \frac{\partial}{\partial x} N_f \\ \frac{\partial}{\partial t} N_\gamma = (\nu_{br} N_f + \nu_{an} N_p)(1-W) - \nu_c N_\gamma - c \frac{\partial}{\partial x} N_f \\ \frac{\partial}{\partial t} N_{i+} = (\nu_f + \nu_s) N_f + \nu_{an} N_p + \nu_{bs} N_p + \nu_c N_\gamma \\ \frac{\partial}{\partial t} N_{i-} = \nu_{at} N_f + \nu_{at} N_s \\ \frac{\partial}{\partial x} E = 4\pi e (N_f + N_s + N_{i-} - N_{i+} - N_p) \end{cases}$$

In oder to estimate the ratio of numbers of different particles, it is convenient to consider a region which is much less than e-folding length. Then the particle concentration in the region could be considered homogeneous. The corresponding quasistationary solution has the following form:

$$\begin{cases} N_s = N_f \frac{1}{\nu_{at}} ((\nu_s + \nu_{br}(1+W)) + \frac{\nu_{br} W^2}{(1-W)}) \\ N_p = N_f \frac{\nu_{br} W}{\nu_{an} \cdot (1-W)} \\ N_\gamma = N_f \frac{\nu_{br} \cdot (1+W)}{\nu_c} \end{cases}$$

Assuming $N_{i-} = N_+$, the electric field distribution is described as follows:

$$\frac{\partial}{\partial x} E = 4\pi e N_f (1 + \frac{(\nu_s + \nu_{br}(1+W))}{\nu_{at}}) + \\ + \frac{\nu_{br} W^2}{\nu_{at}(1-W) - \frac{\nu_{br} W}{\nu_{an} \cdot (1-W)}} \tag{2}$$

Three terms in Eq.2 correspond to the contributions to the vertical component of the electric field derivative from runaway electrons, slow electrons, and positrons. The frequencies of the processes listed above make it possible to estimate the ratio of contributions: $1 : 10^4 : 10^{-1}$ — the contribution due to slow electrons is absolutely predominant. The contribution to the field derivative of each particle type is proportional to the number of particles of this type. Therefore, $N_f : N_s : N_p = 1 : 10^4 : 10^{-1}$, which is in good quantitative agreement with [7].

Avalanche multiplication leads to an exponential increase in the number of avalanche particles [3], on a scale λ dependent on the electric field in the avalanche region [5]. Therefore, a a quasistationary solution corresponding to self-sustaining development of avalanches could be obtained as follows:

$N_f = N_{f0} \cdot e^{\frac{x}{\lambda}}$, $N_p = N_{p0} \cdot e^{\frac{x}{\lambda}}$, $N_\gamma = N_{\gamma 0} \cdot e^{\frac{x}{\lambda}}$, $\lambda = \frac{7300 kV}{|E - E_d|}$, $E_d = 276\ \frac{kV}{m} \times n$.

$$\begin{cases} N_s = N_f \frac{1}{\nu_{at}} ((\nu_s + \nu_{br}(1+W)) + \frac{W(\nu_{br} W + \frac{c}{\lambda})}{(1-W)}) \\ N_p = N_f \frac{(\nu_{br} W + \frac{c}{\lambda})}{\nu_{an} \cdot (1-W)} \\ N_\gamma = N_f \frac{(\nu_{br} W + \frac{c}{\lambda})}{(\nu_c + \frac{c}{\lambda})} \end{cases}$$

The assumption of the existence of a stable electric field structure in which charging currents are compensated by

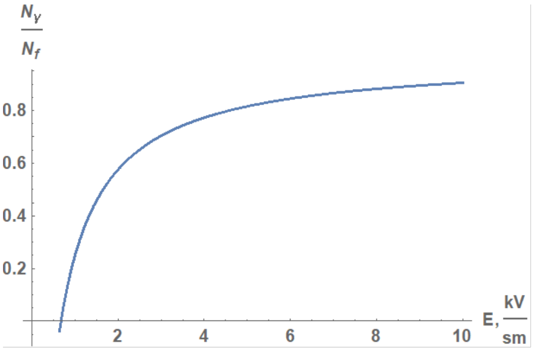

Figure 1. The dependence of the number of gamma rays (relative to the number of fast electrons) on electric field strength.

avalanche currents is based on the fact of observing long lasting gamma-glows and was discussed in [1].

The resulting dependence of the ratio of the number of gamma rays to the number of fast electrons on the electric field is shown at Figure 1. The number of photons differs from the number of runaway electrons by less than 20% for the electric field exceeding 6 $\frac{kV}{sm}$. The obtained relation provides a possibility to estimate the number of photons using a known value of the number of electrons and vice versa. This opportunity is especially important when it is not possible to register one of the types of particles. Moreover, the result is useful for refining the methodology of distinguishing the response of detectors to photons and electrons.

4 Evaluation of electric current of avalanches and conductivity in a cloud

The development of runaway electron avalanches in a cloud leads to the production of free electrons, which is favorable for the initiation of a lightning discharge. Estimation of probability of the formation of a plasma channel due to avalanches development, mentioned in [7], requires a consideration of the conductivity perturbation in the avalanche region. The change in conductivity is determined by the concentration of slow electrons because it greatly exceeds the concentration of fast electrons. The cone angle in which avalanche particles propagate can reach 25 °[5], resulting in lateral size of 900 m for a 1 km long avalanche. A typical number of runaway electrons in one avalanche is $N_f = 10^6$ [8], slow electrons: $N_s = 10^{10}$. The corresponding value of electron concentration in an avalanche is $\rho_s = 10^2$ m^{-1}. The conductivity of the avalanche region could be described by the formula $\sigma = \frac{\rho \cdot e^2}{m \cdot v_{at}}$ and approximaately equals to $10^{-14} Sm^{-1}$, which is close to an average conductivity in a cloud, which depending on humidity and other physical parameters, takes values in the range $10^{-16} \div 10^{-12}$ Sm^{-1}.

The electric current density of one avalanche in an electric field E_{th} is $j = \sigma \cdot E = 10^{-9}$ $A \cdot m^{-2}$. For the avalanche lateral size of 1 km, the total current is $I = 10^{-3}$ A. The total number of avalanches simultaneously existing in the same cloud is of the order of $10^4 \div 10^{13}$ [8]. Therefore, there are always avalanches that are spaced apart from each other by less than the lateral size of the avalanche at its end. Thus, the development of relativistic runaway electron avalanches in a cloud could lead to increase in conductivity by ten orders of magnitude (up to 10^{-4} Sm^{-1} at the end of the strong field region). The integral elecrtric curent of avalanches (up to $I = 10^6$ A, dependent on the electric field and the size of the strong field region) is comparable with the current of the main stage of lightning discharge, and can produce VLF-radiation similar to that of lightning.

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References

[1] J. R. Dwyer, D. M. Smith, S. A. Cummer, “High-Energy Atmospheric Physics: Terrestrial Gamma-Ray Flashes and Related Phenomena,” *J Space Sci Rev*, **173**, 2012, pp. 133–196, doi: 10.1007/s11214-012-9894-0.

[2] A. Chilingarian, “Thunderstorm Ground Enhancements — model and relation to lightning flashes,” *JASTP*, **107**, 2013, 68–76, doi: 10.1016/j.jastp.2013.11.004.

[3] A. V. Gurevich, G. M. Milikh, R. A. Roussel-Dupré, “Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm,” *Phys Lett A*, **165**, 1992, pp. 463–468, doi: 10.1016/0375-9601(92)90348-P.

[4] C. T. R. Wilson, “The acceleration of beta-particles in strong electric fields such as those of thunder-clouds,” *Proc Cambridge Philos Soc*, **22**, 1925, pp. 534–538, doi: 10.1017/S0305004100003236 .

[5] J. R. Dwyer, “The relativistic feedback discharge model of terrestrial gamma ray flashes,” *J Geophys Res*, **117**, 2012, A02308, doi: 10.1029/2011JA017160.

[6] V. A. Rakov, M. A. Uman, “Lightning Physics and Effects,” Cambridge Univ. Press, Cambridge, U. K., 2003.

[7] J. R. Dwyer, L. Babich, “Low-energy electron production by relativistic runaway electron avalanches in air,” *J Geophys Res*, **116**, 2011, A09301, doi: 10.1029/2011JA016494.

[8] J. R. Dwyer, S. A. Cummer, “Radio emissions from terrestrial gamma-ray flashes,” *JGR: Space Phys*, **118**, 2013, pp. 3769–3790, doi:10.1002/jgra.50188.