Modeling hard radiation from streamers and leaders and terrestrial gamma-ray flashes

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Terrestrial gamma-ray flashes are observed above thunderclouds. Energetic radiation is also reported from lightning leaders approaching ground, and it is measured during the initial streamer-leader phase of meter-long spark discharges in the laboratory. We study the generation of such radiation by streamer coronas and leaders and present three results: First, with our numerical hybrid code, we have developed a numerical tool with limited numerical costs that accurately follows the acceleration and run-away of individual electrons from a negative streamer. Second, we present effective differential cross-sections for Bremsstrahlung in air to determine the hard radiation, as well as cross-sections for the production of electron-positron pairs (antimatter). Third, we estimate the X-ray and gamma-ray emission above an upwards propagating negative intracloud leader.

1. Introduction

Terrestrial gamma-ray flashes (TGF's) were recently related to upwards negative leaders in thunderclouds by Cohen et al. [1]. Energetic radiation is also reported from lightning leaders approaching ground [2], and it is measured during the initial streamer-leader phase of meter-long spark discharges in the laboratory [3-6]. We present three theoretical contributions to understanding hard radiation and positron production from leaders and their streamer corona.

1. The path of leaders is paved by a corona of streamer discharges, and we investigate the production of runaway electrons in negative streamers numerically. (We recall that streamers are extremely transient and furthest from equilibrium of the whole discharge process, with a strong field enhancement at its tip.)

2. We review and derive relevant cross-section data for the generation of hard X-rays and Gamma-rays through Bremsstrahlung of energetic electrons in air, in the range both of the lab experiments as well as of TGF's. We also provide data for the generation of electron-positron pairs.

3. We simulate electron run-away in the thundercloud above a lightning leader, as well as emission and direction of energetic photons.

2. Hybrid calculations for streamers and production of keV electrons

We have developed a hybrid simulation code for streamers without too high numerical costs that follows the acceleration of individual electrons in the high field region at the streamer tip. The problem lies in the fact that single electrons have to be followed in the tip, while the system contains too many electrons to follow individually. Therefore in the low field region in the streamer interior, a large number of relatively slow electrons is modeled in density approximation, while the fewer electrons at the tip are followed individually. Where and how to connect particle and density approach, was a major numerical challenge. The approach and the results are described by Li et al. [7-9]. We mention that an alternative approach with weighted super-particles was developed by Chanrion and Neubert [10,11].

In Fig. 1, we reproduce hybrid simulation results for a negative streamer, published originally by [7]. Electrons with energies above 200 eV (at 200 eV the electron friction is maximal) start to appear when the maximal field E at the streamer tip reaches 160 kV/cm (at t~0.36 ns). As the maximal field E increases further during streamer propagation, both the number and the energy of the high energy electrons increases. At t~0.54 ns, electrons with energies above 1 keV are observed. Note that the mean energy of electrons at the streamer head is ~15 eV at this stage. When the streamer later approaches the upper boundary of our simulation domain, electrons reach energies of up to 3.5 keV. We expect that the electrons continue to accelerate if no boundary is present at the upper end of the simulated volume. We believe that this is the reason why Chanrion and Neubert [11] observed higher electron energies in an otherwise similar simulation: their relative system size is larger.

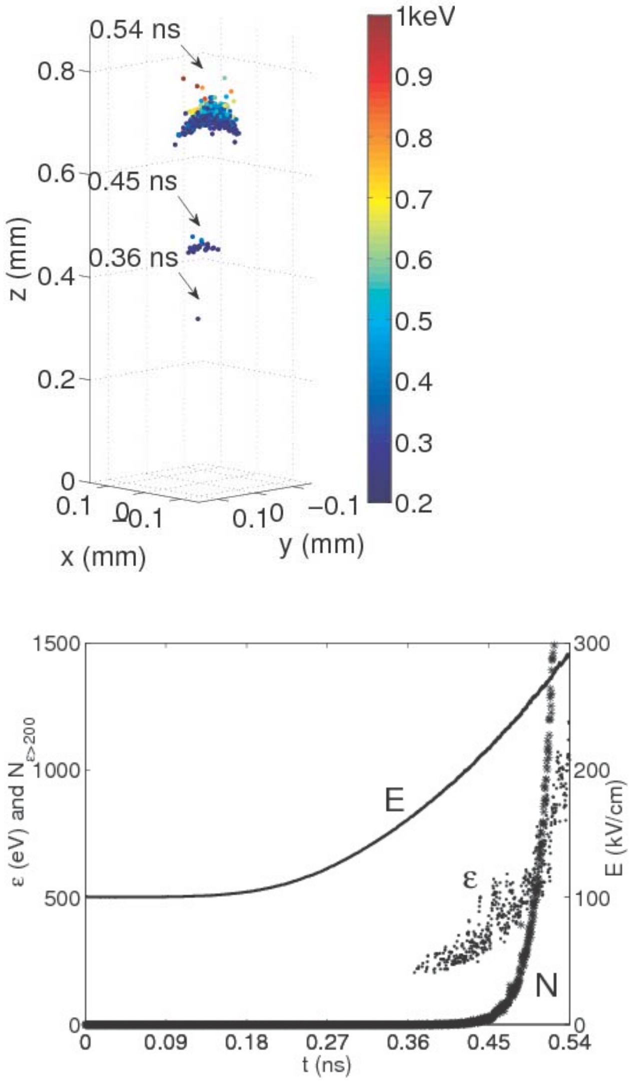

Figure 1: Results of a hybrid simulation of an upward propagating negative streamer, as originally published in [7]. The upper panel shows positions and energies of single electrons with energy above 200 eV at time steps 0.36 ns, 0.45 ns and 0.54 ns; these fast electrons are at the respective tip of the streamer channel, and their energies between 200 eV and 1 keV are color coded. The maximal electric field E at these times is 160, 220, and 290 kV/cm. The lower panel shows the maximal electric field strength E at the streamer tip, the number of electrons N with energy larger than 200 eV, and the highest electron energy ε as a function of time.

3. Differential cross-sections for Bremsstrahlung and pair production

The calculation of X-ray and gamma-ray emissions from fast electrons in air requires appropriate differential cross-sections for the Bremsstrahlung generated when an electron collides with a molecule. Köhn reviewed the literature, performed the necessary integrations and will present the required effective parameters at the conference in the energy range from the (hard) X-rays observed in lab experiments up to TGF's. Energy and angular distributions of photons will be presented relative to energy and direction of the incident electron.

We also provide cross sections for the production of electron positron pairs. For one particular type of pair production the cross section formulas show a so-called cross symmetry to the cross section for Bremsstrahlung so that Bremsstrahlung results can be taken over. Furthermore we have found cross sections for other processes creating positrons; however, these processes seem less likely.

4. Estimating TGF production from upwards propagating negative intracloud leaders

Motivated by the observations of Cohen et al. [1], we simulate the scenario sketched in Fig. 2: A negative leader propagates upwards in a thundercloud field. Its streamer corona is the source of run-away electrons with keV energies (for the production of these photons, see above). These energetic electrons are being accelerated further in the thundercloud field. We calculate the propagation and further acceleration of these electrons in the thundercloud, taking all elastic, inelastic and ionizing scattering events into account. We calculate the energetic and directional distribution of energetic photons and possibly of electron-positron pairs.

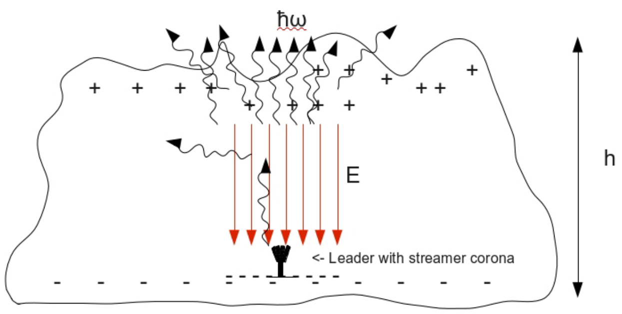

Figure 2: A scenario for the production of TGF's and electron-positron pairs.

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