Energy resolved positron and hadron spectrum produced by a negative stepped lightning leader

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Gamma-ray flashes with quantum energies up to 40 MeV and beams of electrons and positrons have been detected by satellites above thunderclouds. We here adopt the model of an upward moving negative stepped lightning leader by Xu et al. We simulate the generation and dynamics of free electrons, of photons with energies above 1 MeV, of positrons, neutrons and also protons with a three dimensional, relativistic Monte Carlo code. For the photons, we include photoionization, Compton scattering, electron-positron pair production and photonuclear processes. We present the angular distribution and the energy spectrum of positrons and their temporal evolution. We also present the energy spectra of neutrons and protons and show how their energy dissipates. The photon number and spectrum depends on the appropriate Bremsstrahlung processes, and we will show how the inclusion of electron-electron Bremsstrahlung affects the number and energy spectrum of photons and thus the number and energy spectrum of positrons, neutrons and protons.

1. Sources of electrons and photons for the modelling of terrestrial gamma-ray flashes

In thunderstorms and laboratory discharges X- and gamma rays are produced by energetic electrons scattering at air molecules. To produce those high-energy photons, a sufficient number of energetic electrons has to be generated during the discharge process. We will compare three source processes for these electrons: Electron impact ionization [1] where the incident electron ejects a shell electron, electron-nulceus Bremsstrahlung [2] where the incident electron interacts with the nuclei of air molecules and emits a Bremsstrahlung photon, and electron-electron Bremsstrahlung [3] where the incident electron interacts with a shell electron and emits this shell electron and a photon.

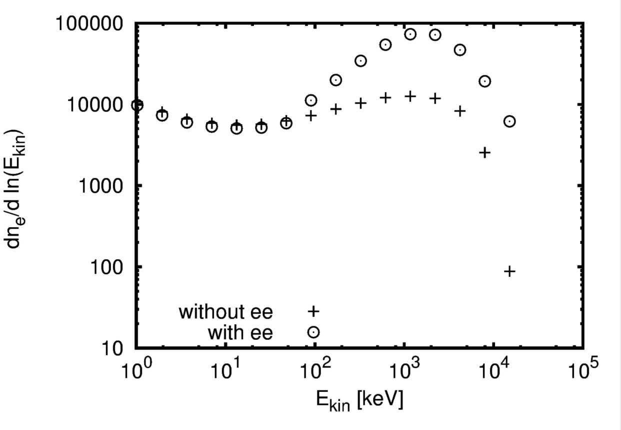

Figure 1: The energy distribution of electrons after 24 ns with (circles) and without (crosses) electron-electron Bremsstrahlung.

In air electron-electron Bremsstrahlung becomes important of electron energies above 10 MeV and for photon energies below 100 eV. However, electron-electron Bremsstrahlung leads to an enrichment of high-energy electrons as the energy of the two resulting electrons is split more evenly than for electron impact ionization. Subsequently the increased number of high-energy electrons leads to an enrichment of high-energy photons [4].

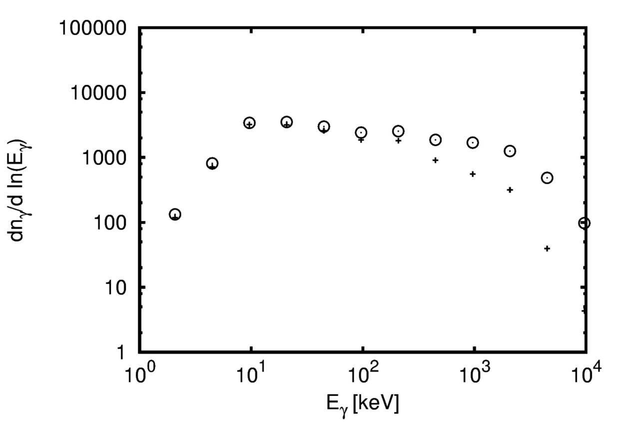

Figure 2: The energy distribution of photons after 24 ns with (circles) and without (crosses) electron-electron Bremsstrahlung.

We have adopted the model of Xu et al [5]. and simulated the motion of electrons in the electric field of a negative stepped lightning leader of 4 km length and 1 cm curvature at 16 km altitude with and without electron-electron Bremsstrahlung. Figure 1 shows that the number of electrons with energies above 100 keV is enlarged through electron-electron Bremsstrahlung; Figure 2 shows the energy distribution of subsequent photons after 24 ns. It shows that due to the enlarged number of high-energy electrons, also the number of photons with energies above 100 keV is larger with electron-electron Bremsstrahlung. This process dominates the distribution for energies above 1 MeV.

2. The generation of positrons and hadrons

The photon distribution appears to saturate after 24 ns. Hence we use the energy distribution as in Fig. 2 as an initial condition to simulate the motion of photons upwards above a thundercloud. If these photons interact with air molecules, they can either create pairs of electrons and positrons through pair production [2] or hadrons (protons and neutrons) [6] through photonuclear processes if their energy is above 1 MeV or 8 MeV, resp. The resultant positron distribution shows kinetic energies from 2 up to 30 MeV. Furthermore, we have calculated the energy resolved angular distribution of positrons and seen that positrons with energies above 1 MeV are mainly emitted in direction of the incident photon.

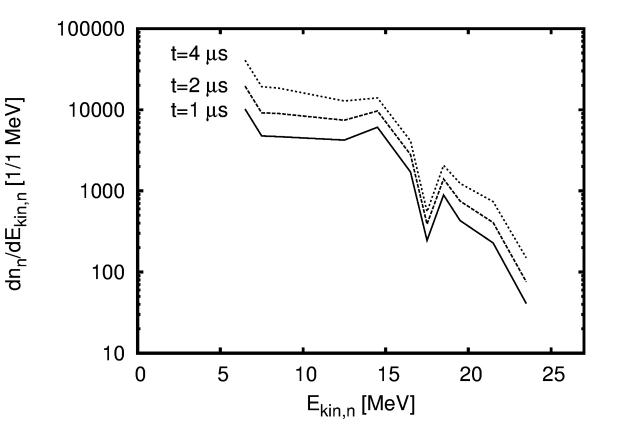

Figure 3: The energy distribution of neutrons after 1 μs, 2 μs and 4 μs; all neutrons are distributed between 16 km and 17.4 km altitude.

Babich [7] has estimated that the average energy of neutrons produced during an upwards atmospheric discharge would be 10 MeV using the relativistic run-away electron avalanche (RREA) theory. Fig. 3 shows the neutron distribution created by a negative stepped lightning leader. The neutron energies reach from 5 MeV up to 24 MeV. The photonuclear cross section for the generation of neutrons has a minimum at approximately 24 MeV; considering a binding energy of 8 MeV per nucleon in nitrogen, this leads to the minimum at approximately 16 MeV in the neutron distribution. The dip at approximately16 MeV comes from a minimum of photonuclear cross sections at 24 MeV where 8 MeV is the

Subsequently we model the motion of positrons and hadrons upwards through air. We will show that the number of all three species will not change significantly and also their energy will not change considerably. Thus they can be detected above thunderclouds.

3. References

[1] Y. K. Kim, J.P. Santos, Extension of the binary-encounter-dipole model to relativistic incident electrons, Phys. Rev. A 62 (2000) 052710.

[2] C. Koehn, U. Ebert, Angular distribution of Bremsstrahlung photons and of positrons for calculations of terrestrial gamma-ray flashes and positron beams, Atmos. Res. 135-136 (2014) pp. 432-465.

[3] F. Tessier, I. Kawrakow, Calculation of the electron-electron bremsstrahlung cross-section in the field of atomic electrons, NIM. Phys. Res. B 266 (2007) pp. 625-634.

[4] C. Koehn, U. Ebert, A. Mangiarotti, The importance of electron-electron Bremsstrahlung for terrestrial gamma-ray flashes, electron beams and electron-positron beams, Submitted to J. Phys. D: Appl. Phys. (2014).

[5] W. Xu, S. Celestin, V.P. Pasko, Source altitudes of terrestrial gamma-ray flashes produced by lightning leaders, Geophys. Res. Lett. 39 (2012) L08801.

[6] E.G. Fuller, Photonuclear reaction cross sections for ^{12}C, ^{14}N and ^{16}O, Phys. Rep. 127 (1985) pp. 185-231.

[7] L.P. Babich, Neutron generation mechanism correlated with lightning discharges, Geomag. and Aero. 47 (2007) pp. 664-670.