Cross sections and modelling results for high-energy radiation and positron beams produced within a thundercloud

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Satellite measurements have revealed that thunderclouds emit flashes gamma-rays (terrestrial gamma-ray flashes/TGFs) and beams of electrons and positrons. We model the energy resolved angular distribution of these beams produced by a negative lightning leader stepping upwards in a thundercloud. First we present our results for doubly differential cross sections for Bremsstrahlung and pair production based on the triply differential cross-sections of Bethe and Heitler. Other cross sections in literature and databases do not cover the appropriate energy range or do not apply to the small atomic numbers of nitrogen and oxygen or do not resolve both energies and emission angles of emitted photons or positrons. Second we have extended a Monte Carlo model designed for streamer modelling towards relativistic electron energies, and we have included the new cross sections as well as Compton scattering of photons and photo ionization.

1. High-energy radiation and positron beams from thunderclouds

In 1994 the BATSE satellite measured flashes of gamma-rays (Terrestrial gamma-ray flashes/TGFs) above thunderstorms [1]. Recent measurements have shown that these flashes can have energies up to 40 MeV.

In 2011 NASA's Fermi satellite detected positron beams above Egypt [2] which were produced in a thunderstorm above Sambia. Since positrons are charged particles they move along the geomagnetic field lines above the atmosphere, directly towards the satellite.

The underlying mechanisms how hard radiation and positrons are created in air are Bremsstrahlung and pair production.

2. Cross sections for Bremsstrahlung and pair production relevant for terrestrial thunderstorms

If electrons scatter on the neutrals of the background gas, they can produce hard Bremsstrahlung photons. The Bethe Heitler cross section for Bremsstrahlung [3] is appropriate for a large energy range for the constituents of air as they have nuclei with a small atomic number Z. The triply differential cross section of Bethe and Heitler parameterizes all the energies and all the relevant angles of incident and scattered electron and of the generated photon. We need to resolve both relative angle and energy of an emitted energetic photon; therefore we have analytically integrated out the angles parametrizing the scattered electron in [4] and derived the required doubly differential cross-section.

This information was previously not available. As we discuss in [4], other literature and databases, do not deliver the necessary information. Either they do not give the correlation between photon energy and emission angle, or they do not cover the needed energy range or the required range of small atomic numbers.

The Bremsstrahlung photons can interact with the neutrals and ions of the background gas and produce electron positron pairs, if they have sufficient energy. The cross section for pair production in the field of a nucleus shows a quantum-physical symmetry to that of Bremsstrahlung [3]; thus we can use the results for Bremsstrahlung and obtain a correlation between positron energy and its emission angle relative to the direction of Bremsstrahlung photons.

3. Simulation of TGFs and positrons produced by a negative stepped lightning leader

Lightning observations showed that lightning also moves stepwise. We model a negative stepped lightning leader with length L = 4 km and radius r = 1 cm on the tip at 16 km altitude moving upwards in a thundercloud; we use an ambient field of $E_0 = 0.5$ kV/cm which is similar to [5]. While the leader steps [6], electrons are accelerated from the surface of the leader by the high field ahead of it. We have simulated these electrons with a Monte Carlo code. We start from a code that was designed to simulate the initiation and motion of streamers [7,8] and have extended it with relativistic equations of motion and cross sections for ionization and elastic scattering (also for relativistic energies). Electrons accelerated from the tip ionize the background gas and a cloud of electrons forms. We also include our results for Bremsstrahlung. In our model we treat the produced photons as particles and take into account Compton scattering, pair production, photo ionization and Rayleigh scattering. We obtain the correlation between a negative stepped leader propagating upwards and the production of TGFs and positrons. Furthermore the direction of the photons and the positrons will be related to their energy. We will present the energy spectrum of electrons and photons for different time steps as in Figure 1. We will show that most electrons and photons have energies in the eV range, but that some of them can reach energies in the MeV range.

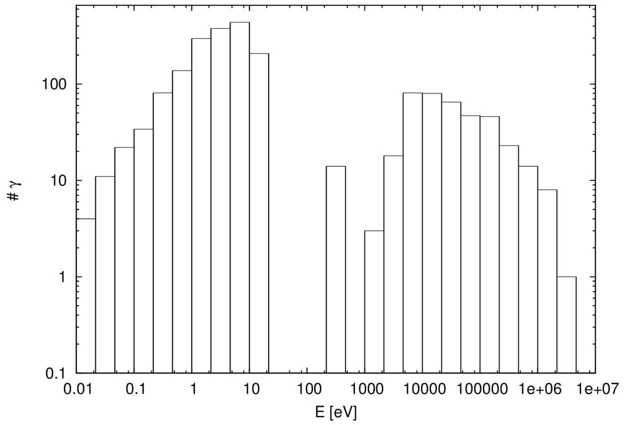

Figure 1: The energy spectrum of Bremsstrahlung photons produced by a negative stepped lightning leader after t = 24 ns.

First we trace both electrons and photons before we only trace photons since their we want to get the fast TGF signal at 500 km altitude. There, satellites measure the emitted gamma-rays. We obtain the energy spectrum of photons and compare our results with the results previously measured by satellites.

We also included a simple model for the geomagnetic field and show its influence on the energy spectra of electrons and photons.

4. Bremsstrahlung photons from a laboratory discharge

Our model is also applicable to simulate the production of hard X-rays in streamer and leader discharges produced with Marx generators in the Megavolt range [9]. In experiments it is observed that streamers emit X-rays. When a discharge is initiated, an inception cloud forms [10,11] through ionization where electrons collide with the background gas. We use our Monte Carlo code and apply our Bremsstrahlung cross sections to obtain the spectrum of photons produced in an inception cloud.

5. References

[1] G.J. Fishman et al., 1994. *Discovery of intense gamma-ray flashes of atmospheric origin.* Science, vol. 264, pp. 1313-1316.

[2] M.S. Briggs et al., 2011. *Electron-positron beams from terrestrial lightning observed with Fermi GBM.* Geophys. Res. Lett., vol. 38, L02808.

[3] H.A. Bethe and W. Heitler, 1934. *On the stopping of fast particles and on the creation of positive electrons.* Proc. Phys. Soc. London, vol. 146, pp. 83-112.

[4] C. Koehn and U. Ebert, *Angular distribution of Bremsstrahlung photons and of positrons for calculations of terrestrial gamma-ray flashes and positron beams,* to appear in "Atmospheric Research", preprint available on http://arxiv.org/abs/1202.4879

[5] W.Xu et al., 2012. *Source altitudes of terrestrial gamma-ray flashes produced by lightning leaders*. Geo. Res. Let., vol. 39, L08801

[6] I. Gallimberti, 2002. *Fundamental processes in long air gap discharges*. C. R. Physique, vol. 3, pp. 1335-1359.

[7] C. Li et al., 2009. *3D hybrid computations for streamer discharges and production of runaway electrons*, J. Phys. D-Appl. Phys., vol. 42, no. 202003

[8] C. Li et al., 2012. *Spatially hybrid computations for streamer discharges: II. Fully 3D simulations,* J. Comput. Phys., vol. 231, pp. 1020-1050.

[9] P. O. Kochkin et al., 2012. E*xperimental study of hard x-rays emitted from metre-scale positive discharges in air*. J. Phys. D-Appl. Phys., vol. 45, no. 42502

[10] T. T. J. Clevis, S. Nijdam and U. Ebert, 2013. *Inception and propagation of positive streamers in high-purity nitrogen: effects of the voltage rise rate*. J. Phys. D-Appl. Phys., vol. 46, no. 045202

[11] L. Heijmans, S. Nijdam et al., 2013. *Investigation of the inception cloud of positive streamers*. Abstract contributed to this conference.