Theory and modeling of X- and gamma-ray emission from lightning

S. Celestin[1]

[1]*LPC2E, University of Orleans / CNRS, Orleans, France*

This topical lecture will focus on a recently uncovered field of study that belongs to the area of high-energy atmospheric physics, namely the production of high-energy radiation from lightning discharges. In the present abstract, we outline some important concepts that will be developed during the lecture, along with some relevant references.

1. Introduction

X-rays emissions have been recently discovered in correlation with natural [1, 2] and rocket-triggered lightning discharges [3, 4]. More specifically, negative cloud-to-ground lightning is known to produce copious amounts of X- and gamma-rays observed from the ground during the propagation stage of lightning leaders through air and during subsequent strokes (e.g., [2, 5, 6]).

Terrestrial Gamma ray Flashes are very brief intense bursts of gamma-rays detected by space-borne (and recently air-borne [7]) instruments that could be directly produced by high-potential intracloud negative lightning leaders [8-11].

Additionally, X-ray emissions from discharges in laboratory experiments have been widely documented and new physical processes put forward (e.g., [12-17] and references therein).

2. Theoretical description of the production of high-energy electrons by atmospheric discharges

2.1. Thermal runaway electrons

A key concept in the production of X-rays by atmpospheric discharges is that of the "runaway" electron acceleration. Runaway electrons are electrons with high energy and therefore low probability of collision with gas molecules, propagating in an applied electric field so that the energy they acquire from the field is higher than the energy losses due to collisions. These electrons are therefore capable of efficiently gaining energy from an electric field in air. One can distinguish between thermal runaway processes, for which a very high electric field ($>E_c \simeq 240$ kV/cm in air at ground pressure) exceeds the friction force at low-energy (~100 eV) and brings electrons to regimes where they continuously accelerate, and relativistic runaway processes [18] for which initial high-energy electrons are already present (e.g., cosmic ray secondary electrons) and can initiate relativistic runaway electron avalanches (RREAs) in electric fields higher than $E_t \simeq 2.8$ kV/cm in air at ground pressure (e.g., see [19]).

X-ray bursts from lightning discharges have been clearly identified to stem from the production of thermal runaway electrons [20].

2.2. Atmospheric discharges

Streamers represent a common electrical breakdown process at ground-level atmospheric pressure. They are filamentary discharges propagating as ionizing waves. The enhancement of electric fields around streamer fronts is one of the unique naturally occurring circumstances in which the electric field in air can approach one order of magnitude above the conventional breakdown threshold field defined by the equality of the ionization and dissociative attachment coefficients in air (~30 kV/cm at ground level). In streamer fronts, these extreme electric fields can be dynamically produced and sustained for relatively extended periods of time. Thus, streamers represent solid candidates for the production of thermal runaway electrons. Moreover, laboratory experiments have demonstrated that streamers do indeed emit X-rays (see Introduction section). However, streamers usually possess potential drops limited to a few tens of kilovolts, and although they are key to seeding runaway electrons, other acceleration processes need to be involved to explain observations of photons with energies in the MeV range [9].

Streamers play a very important role in lightning leader propagation (e.g., [21]). Leader tips are usually shielded by a high number of streamers in regions named "streamer zones." Additionally, is recognized that negative leaders propagate by steps. With the occurrence of each new step, the leader tip is left uncovered and high electric fields can extend

over significant lengths in front of the leader tip. This gives rise to a highly transient process named "negative corona flash," in which newly produced streamers are building up a new streamer zone. Initiated in this leader field, runaway electrons injected from streamer tips near the leader tip can further accelerate to energies on the order of several tens of MeVs, depending on the particular magnitude of the potential drop in the vicinity of the leader tip [8-11]. Indeed, X-ray bursts are associated in time with the stepping processes in lightning leaders [2].

3. Modeling the propagation of high-energy electrons and photons through air

When propagating in molecular gases, electrons are involved in various kinds of collisions (elastic and inelastic, including vibrational, rotational, and electronic excitations, and ionization) that modify their propagation dynamics. To quantitatively characterize the production and dynamics of thermal runaway electrons accelerated through an electric field in a dense medium, like ground-level air, one needs to develop a model that is relativistic, spans over a very broad range of energy (sub-eV to several tens of MeVs), and contains a careful description of the various collision types over this energy range (e.g., [9, 22]).

Energetic electrons produce X- and gamma-rays when propagating through air via bremsstrahlung processes.

Once high-energy photons are produced, their propagation through air can be modeled by taking into account three types of collisions: Photoelectric absorption, Compton scattering, and electron-positron pair production.

The production and transport of electrons and photons can be modeled using Monte Carlo codes [8, 9, 23].

4. Acknowledgments

The related research work is supported by the French Space Agency (CNES).

5. References

[1] Moore, C. B., K. B. Eack, G. D. Aulich, and W. Rison (2001), Geophys. Res. Lett., 28, 2141.

[2] Dwyer, J. R., et al. (2005), Geophys. Res. Lett., 32, L01803.

[3] Dwyer, J. R., et al. (2003), Science, 299, 694.

[4] Saleh, Z., J. Dwyer, J. Howard, M. Uman, M. Bakhtiari, D. Concha, M. Stapleton, D. Hill, C. Biagi, and H. Rassoul (2009), J. Geophys. Res., 114, D17210.

[5] Schaal, M. M., et al., (2012), J. Geophys. Res., 117, D15201.

[6] Mallick, S., V. A. Rakov, and J. R. Dwyer (2012), J. Geophys. Res., 117, D16107.

[7] Smith, D. M., et al. (2011), J. Geophys. Res., 116, D20124.

[8] Moss, G., V. P. Pasko, N. Liu, and G. Veronis (2006), J. Geophys. Res., 111, A02307.

[9] Celestin, S., and V. P. Pasko (2011), J. Geophys. Res., 116, A03315.

[10] Xu, W., S. Celestin, and V. P. Pasko (2012), Geophys. Res. Lett., 39, L08801.

[11] Celestin, S., W. Xu, and V. P. Pasko (2012), J. Geophys. Res., 117, A05315.

[12] Babich, L. P. (1982), Sov. Phys. Dokl., Engl. Transl., 27, 215.

[13] Dwyer, J. R., H. K. Rassoul, Z. Saleh, M. A. Uman, J. Jerauld, and J. A. Plumer (2005), Geophys. Res. Lett., 32, L20809.

[14] Rahman, M., V. Cooray, N.A.Ahmad, J.Nyberg, V. A. Rakov, and S. Sharma (2008), Geophys. Res. Lett., 35, L06805.

[15] Nguyen, C. V., A. P. J. van Deursen, and U. Ebert (2008), J. Phys. D Appl. Phys., 41, 234012.

[16] Nguyen, C. V., A. P. J. van Deursen, E. J. M. van Heesch, G. J. J. Winands, and A. J. M. Pemen (2010), J. Phys. D Appl. Phys., 43, 025202.

[17] P. O. Kochkin, C. V. Nguyen, A. P. J. van Deursen, and U. Ebert (2012), J. Phys. D: Appl. Phys., 45, 425202.

[18] Gurevich, A. V., G. M. Milikh, and R. A. Roussel-Dupré (1992), Phys. Lett. A., 165, 463.

[19] Dwyer, J. R., D. M. Smith, and S. A. Cummer (2012), Space Sci. Rev., 173, 133.

[20] Dwyer, J. R. (2004), Geophys. Res. Lett., 31, L12102.

[21] Bazelyan, E. M., and Y. P. Raizer (2000), IoP Ltd., Bristol, U. K.

[22] Celestin, S., and V. P. Pasko (2010), J. Phys. D: Appl. Phys. 43 315206.

[23] Østgaard, N., T. Gjesteland, J. Stadsnes, P. H. Connell, and B. Carlson (2008), J. Geophys. Res., 113, A02307.