Theoretical Investigation of the Variability in Terrestrial Gamma-ray Flashes Spectra

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Abstract

Terrestrial Gamma-ray Flashes (TGFs) are high-energy photon bursts originating from the Earth's atmosphere and detected from space. In this work, we show how different electric potentials in TGF-producing lightning lead to an intrinsic variability in TGF spectra. This prediction can be exploited to discriminate which one of the two proposed source mechanisms is truly responsible for the production of TGFs.

1. Introduction

Terrestrial Gamma-ray Flashes (TGFs) are high-energy photon bursts originating from the Earth's atmosphere [1]. Observations have correlated TGFs with initial development stages of normal polarity intracloud lightning that transports negative charge upward (+IC) (e.g., [2]).

Moreover, Tavani et al. [3] have recently reported that the high-energy part (>30 MeV) of the TGF spectrum, measured by the AGILE mission for the first time, significantly deviated from spectra corresponding to well-established model of relativistic runaway electron avalanches (RREAs), which so far provided a very good agreement with observations at lower energies [4]. Additionally, Tavani et al. [3] discovered photons in the high-energy tail of terrestrial gamma-ray flashes with energies up to 100 MeV.

In addition to space-based measurements, X-ray and gamma-ray bursts from lightning discharges have also been observed [5]. These X-ray and gamma-ray bursts have been linked to the production of high-energy electrons, so-called runaway electrons, in the Earth's atmosphere. Runaway electrons are electrons with high energy and consequently 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 exceeds the friction force at low-energy (>100 eV) and brings electrons to regimes where they continuously accelerate ($E > E_c \simeq 240$ kV/cm in air at ground pressure), and relativistic runaway processes [6] 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., [7]).

X-ray bursts from lightning discharges have been clearly identified to stem from the production of thermal runaway electrons [8] and TGFs have been suggested to be related to thermal runaway processes in lightning leader tips [9]. However, until recently, TGF spectra were very well reproduced by RREA models involving acceleration of runaway electrons in large-scale (at least several hundreds of meters) weak electric fields in thunderstorms [4].

It has been theoretically shown that RREAs in homogeneous electric fields produce a characteristic exponential high-energy cutoff (~7 MeV) in the electron energy distribution function. This property should therefore be present in the bremsstrahlung photon spectra produced from RREAs and observed from low-orbit satellites [4], if one disregards AGILE's observation of high-energy TGFs. This spectral signature is thought to depend weakly on the exact magnitude of the large-scale electric field in thunderstorms. However, the gamma-ray detectors on board satellites observing TGFs have been designed to study celestial sources and so far possess instrumental limitations, including saturation (dead time and pile-up) and too small effective areas to render a spectrum for each detected TGF. Consequently, comparisons between theoretical models and observations have been performed on the basis of cumulative spectra corresponding to a superposition of all TGF events, washing out the possible intrinsic variability of TGFs spectra. Future space missions such as ASIM of the European Space Agency (ESA) and TARANIS of the French Space Agency (CNES) are being designed to study TGFs from the ground up, and therefore should avoid instrumental limitations. They might reveal instrinsic variability in TGF spectra.

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As mentioned, RREAs in large-scale thundercloud electric fields involve a very stable photon spectrum that could hardly produce much variability above a few megaelectron-volts. However, lightning-produced TGFs [9] would present more complex spectra directly related to the electric potential drop in front of the lightning leader tip [10]. They might also significantly depart from the classic RREA spectrum when a time dynamics is considered [11].

It is the goal of the present paper to investigate theoretically the intrinsic variability in photon spectra produced by lightning discharges in a consistent way from X-ray bursts emitted during the propagation of cloud-to-ground lightning (-CGs) up to TGFs produced by very high potential intracloud discharges (+ICs). This study connects characteristics of X-ray and TGF spectra with the electrical properties of the causative lightning discharges.

2. Model Formulation

2.1 Method of Moments

We use the method of moments in order to calculate the electric field in the vicinity of a lightning negative leader tip at the very beginning of the so-called negative corona flash (see [11] and references therein). The negative corona flash corresponds to the production of a powerful streamer corona right after the completion of a new leader step, and the extreme electric fields produced in the streamer heads during the corona flash are responsible for the production of thermal runaway electrons [9] (see Figure 1). The method of moments allows for computing the electric field produced by an equipotential perfectly conducting leader channel of length l immersed in an ambient thundercloud electric field E_0. The method of moments is a quasi-static approximation, which is valid only if the electric potential in the new leader step rises fast enough so that the electric field is not shielded by the space charge of the corona.

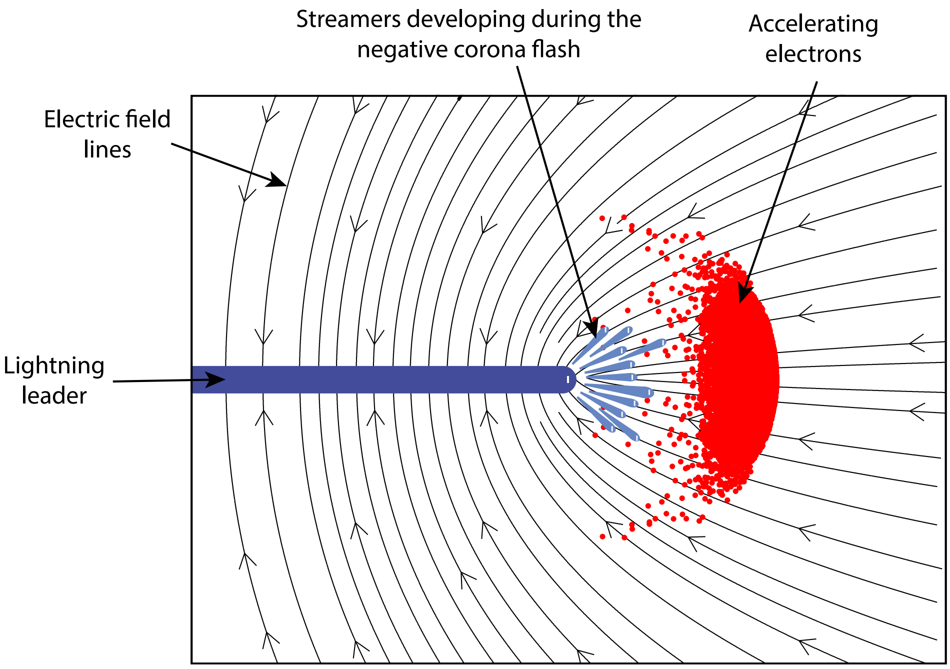

Figure 1. Sketch of the production of thermal runaway electrons and their acceleration in the lightning leader field during the negative corona flash process.

Specifically, the method of moments is used to invert the integral equation of the electric potential in order to solve for the charge distribution along the leader channel. The charge is distributed so that the electric potential in the leader compensates the ambient potential variation due to E_0, preserving equipotentiality of the leader channel. Once the charge density is obtained, the electric field produced by the leader channel can be easily calculated. The electric potential of one lightning leader tip with respect to the ambient potential is approximately $U_l = E_0 l/2$. The radius of the leader channel is chosen as 1 cm, and the lightning length and the magnitude of the ambient electric field are taken so that they yield the potential drop considered.

2.2 Monte Carlo Model for Electrons

The Monte Carlo model we have developed simulates the propagation and collisions of electrons in air (80% N_2 and 20% O_2) under an applied electric field [9]. This model is three-dimensional (3-D) in the velocity space, 3-D in the configuration space, relativistic, and simulates electrons with energies from sub-eV to GeV. The singly differential cross sections of ionization of N_2 and O_2 are calculated over the full range of energy through the relativistic binary-encounter-Bethe model [12]. The knowledge of this differential cross section allows to obtain the energy of the secondary electrons after ionizing collisions. The scattering angles of primary and secondary electrons are then obtained from the relativistic equations of conservation of momentum and energy considering that the newly formed ion is static. We also introduce a continuous radiative friction of electrons due to bremsstrahlung [13].

3. Results and Discussion

The reported results are obtained using initial runaway electrons with energy of 65 keV that are placed in the vicinity of the lightning leader tip. The initial energy is chosen to be 65 keV for consistency with the energy that can be gained by thermal runaway electrons produced by streamer discharges forming the corona flash [9]. Starting from this location, the runaway electrons accelerate in the inhomogeneous field produced by the momentarily unshielded head of the leader and experience various kinds of collisions with the air molecules (see Figure 1). While the RREA process takes place over very large distances in an ambient electric field, which leads to a steady state of the distribution function, the runaway electrons accelerating in the vicinity of a lightning leader tip can only gain a limited kinetic energy due to the limited electric potential difference between the leader and the ambient potential. Therefore, the energy distribution of lightning produced runaway electrons is intrinsically in a transient state. Consequently, one expects that the respective bremsstrahlung photon spectra possess an intrinsic variability that is related to the electrical properties of the causative lightning discharge.

Figure 2a shows the electron energy distribution function weighted by the number of electrons and integrated over the duration of the electron acceleration and deceleration (from the injection of intial electrons up to the moment all electrons have energies lower than 10 keV) for four different potential drops in the vicinity of the lightning leader tip. One can clearly see significant differences obtained between these four cases. The 5 MV (l=1 km, E_0=10^4 V/m) and 10 MV (l=1 km, E_0=$2 \cdot 10^4$ V/m) cases can reproduce the properties of ground-based observed X-ray bursts during the propagation of –CGs, while the 100 MV (l=4 km, E_0=$5 \cdot 10^4$ V/m) and 200 MV (l=4 km, E_0=10^5 V/m) potential differences can be produced by relatively long intracloud discharges [14] and are consistent with TGF observations by RHESSI [10]. The duration of the electron acceleration and deceleration stages varies from ~30 ns in the 5 MV case to ~0.5 μs in the 200 MV case. Note that these durations do not necessarily correspond to the physical duration of the TGF source, which would be related to the duration of runaway electrons injection by streamers forming the corona flash.

Figure 2b shows the bremsstrahlung photon spectrum at the source location produced by electrons corresponding to the distributions presented in Figure 2a. We emphasize that these spectra are strongly modified by the propagation of the photons through air between the source location and the detector, depending on specific observational geometry.

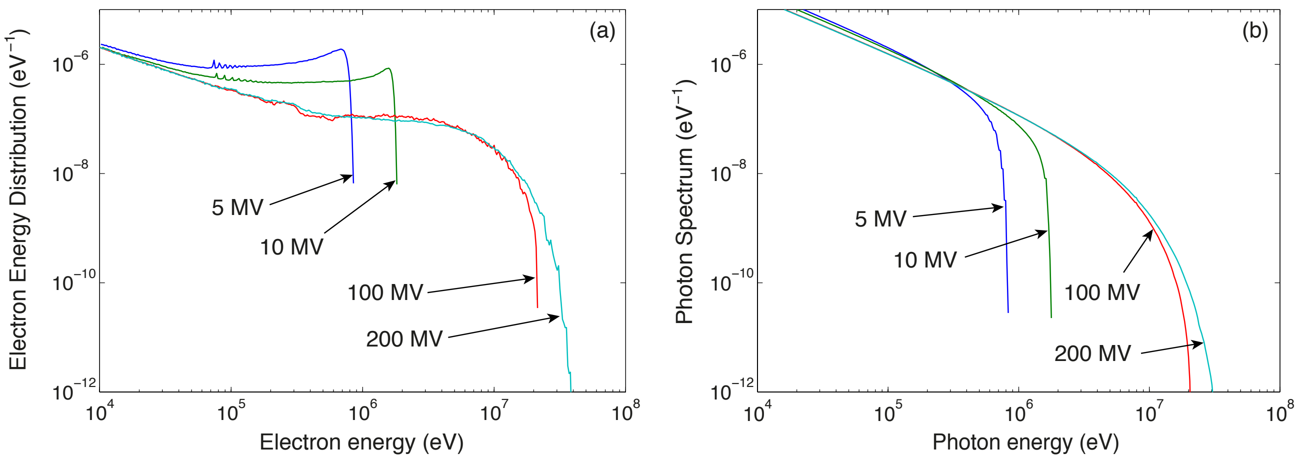

Figure 2. (a) Time integrated electron energy distributions produced by the acceleration of thermal runaway electrons in lightning-leader-produced electric fields with given electric potential drops. (b) Corresponding bremsstrahlung photon spectra.

4. Conclusions

Two mechanisms have been proposed to explain the production of terrestrial gamma-ray flashes (TGFs) in thunderstorm: the relativistic runaway electron avalanches (RREA) in large-scale electric fields and the acceleration of thermal runaway electrons in the vicinity of lightning leader tips during negative corona flash processes. In this work, we have shown that although the RREA mechanism is expected to produce an almost undeviating spectrum for a large range of ambient parameters, the acceleration of thermal runaway electrons by lightning discharges would produce a photon spectrum highly dependent on the electric potential drop in the vicinity of the leader tip. This is a difference of great importance between the two theories that can be exploited, as this variability in TGF spectra should be observed from satellites, even though only TGFs produced by lightning with the highest potentials could be detected. Moreover, this study makes a connection between TGFs characteristics and intrinsic electrical properties of lightning discharges.

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6. References

1. G. J. Fishman et al., “Discovery of intense gamma-ray flashes of atmospheric origin,” *Science*, 264, 1994, 1313.

2. G. Lu, S. A. Cummer, J. Li, F. Han, D. M. Smith, and B. W. Grefenstette, “Characteristics of broadband lightning emissions associated with terrestrial gamma ray flashes,” *J. Geophys. Res.*, **116**, 2011, A03316.

3. M. Tavani et al., “Terrestrial gamma-ray flashes as powerful particle accelerators,” *Phys. Rev. Lett.*, **106**, 2011, 018501.

4. J. R. Dwyer and D. M. Smith, “A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations,” *Geophys. Res. Lett.*, **32**, 2005, L22804.

5. J. R. Dwyer et al., “X-ray bursts associated with leader steps in cloud-to-ground lightning,” *Geophys. Res. Lett.*, **32**, 2005, L01803.

6. A. V. Gurevich, G. M. Milikh, and R. A. Roussel-Dupré, “Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm,” *Phys. Lett. A.*, **165**, 1992, 463-468.

7. J. R. Dwyer, “Source mechanisms of terrestrial gamma-ray flashes,” *J. Geophys. Res.*, **113**, 2008, D10103.

8. J. R. Dwyer, “Implications of X-ray emission from lightning,” *Geophys. Res. Lett.*, **31**, 2004, L12102.

9. S. Celestin and V. P. Pasko, “Energy and fluxes of thermal runaway electrons produced by exponential growth of streamers during the stepping of lightning leaders and in transient luminous events,” *J. Geophys. Res.*, **116**, 2011, A03315.

10. W. Xu, S. Celestin, and V. P. Pasko, “Source altitudes of terrestrial gamma-ray flashes produced by lightning leaders,” *Geophys. Res. Lett.*, **39**, 2012, L08801.

11. S. Celestin, W. Xu, V. P. Pasko, “Terrestrial gamma ray flashes with energies up to 100 MeV produced by nonequilibrium acceleration of electrons in lightning,” *J. Geophys. Res.*, **117**, 2012, A05315.

12. S. Celestin and V. P. Pasko, “Soft collisions in relativistic runaway electron avalanches”, *J. Phys. D Appl. Phys.*, **43**, 2010, 315206.

13. Berger, M. J., J. S. Coursey, M. A. Zucker, and J. Chang, “Stopping-Power and Range Tables for Electrons, Protons, and Helium Ions,” August 2005, Natl. Instit. of Stand. And Technol., Gaithersburg, Md.

14. S. A. Mallios, S. Celestin, and V. P. Pasko, “Production of very high potential differences by intracloud lightning discharges in connection with terrestrial gamma ray flashes,” *J. Geophys. Res.*, **118**, 2013, pp. 912-918.