Optical Emissions Associated with Terrestrial Gamma-ray Flashes

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Abstract

In this paper, we present modeling studies on optical emissions resulting from the excitation of air molecules produced by the large population of electrons involved in TGF events based on two production mechanisms: relativistic runaway electron avalanches (RREA) and production of thermal runaway electrons by high-potential +IC lightning leaders. Numerical models used in this study are first validated through comparison with available laboratory observations. Using Monte Carlo simulations, we show that electron energy distributions established from the two TGF production mechanisms are inherently different over the full energy range, mainly because of the difference in the driving electric fields. Furthermore, we show that TGFs are most likely accompanied with detectable levels of optical emissions. We also demonstrate that, due to the fundamental difference in the acceleration and avalanche multiplication processes undergone by runaway electrons, optical emissions generated by the two viable TGF production mechanisms are intrinsically different. These distinct optical features are of significant interests for constraining and validating current TGF production models.

1. Introduction

Brief and intense photon bursts that originate from the Earth's atmosphere, known as terrestrial gamma-ray flashes (TGFs), were first discovered in 1994 by the Burst and Transient Source Experiment (BATSE) detector aboard the Compton Gamma-Ray Observatory [1]. Space-borne measurements indicate that TGFs typically consist of single or multiple pulses, last from a few tens of microseconds to a few milliseconds [2], and exhibit energy spectra extending up to tens of MeV [3]. Observational evidence is mounting that TGFs are closely associated with the initial development stages of normal polarity intracloud lightning that transports negative charge upward (+IC). Moreover, dedicated analyses have been performed on the initial breakdown (IB) stage of 10 IC flashes that emitted radio signals similar to TGF-producing ones and it has been speculated that the initial leader, due to the large amount of charge at its tip, is capable of sustaining the avalanches of relativistic runaway electrons and thus generating TGFs [4].

Two main mechanisms have been so far proposed and developed for interpreting TGF observations. The first mechanism is that of relativistic runaway electron avalanches (RREAs), which involves acceleration and multiplication of relativistic seed electrons under the large-scale weak electric fields within thunderstorm [5]. The other viable mechanism is based on production of thermal runaway electrons during negative corona flash stage of stepping high-potential lightning leaders [6]. Modeling studies in [7, 8] support this mechanism by demonstrating that further acceleration of these thermal runaway electrons in the electric field produced near the tip region of long unbranched +IC lightning leaders can provide consistent results with satellite measurements of TGF spectra.

In spite of numerous experimental and theoretical efforts, little observational knowledge is available about the TGF source. One of the most important unknowns is if and how measurable optical emissions are produced during the production of TGFs. Optical emissions usually provide insightful knowledge about the energetics of electrons and the driving electric field in the discharge region and are therefore extensively used in the study of Transient Lumious Events (TLEs). Recently, Østgaard *et al.* [9] have reported optical emissions, detected for the first time, by the Lightning Imaging Sensor (LIS) on the Tropical Rainfall Measuring Mission (TRMM), from TGF-associated IC flashes. Based on high-speed camera observations, it has been suggested that the impulsive breakdown associated with initial leaders during IB stages of cloud-to-ground (CG) and IC flashes can generate considerable amount of visible light [10]. Furthermore, studies [11] on optical emissions produced by relativistic feedback discharges indicate that little visible light is emitted during production of TGFs. These observations motivate the present study to quantify the optical emissions generated by the large population of high- and low-energy electrons involved in TGF events.

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2. Optical Emission Simulation

We study the dynamics of electrons in either large-scale homogeneous electric field producing RREAs or the inhomogeneous electric field around lightning leader tip region during negative corona flash stage. Optical emissions arising from the large ensemble of electrons in TGFs are calculated with the knowledge of the distribution of electrons in the full energy range and cross sections of electron-impact excitation collisions. The Monte Carlo model used in the present study to simulate the propagation and collisions of electrons in air is similar to that described in [6]. This model is three-dimensional (3-D) in the velocity space, 3-D in the configuration space, relativistic, and simulates electrons from sub-eV to GeV. The numerical model employed for evaluating the optical emissions resulting from the excitation of air molecules is similar to that documented in [12]. Particularly, we focus on investigating optical emissions from the first ($1PN_2$) and second ($2PN_2$) positive band systems of N_2 and the first negative band system of N_2^+ ($1NN_2^+$).

3. Comparison with Laboratory Observations

In order to perform a comparison on the present numerical models, fluorescence emissions produced by a continuous beam of 50 keV electrons are consistently calculated in the framework of Monte Carlo simulation and compared to laboratory observations [13]. One of the advantages that is afforded by the current Monte Carlo model is that it is capable of accurately describing and recording the spatial and temporal information for all the collisions taking place in this system. Owing to this advantage, the photograph of fluorescence from air generated by a continuous beam of 50 keV electrons at ground pressure can be derived from first principles and is shown in Figure 1. As clearly shown in this figure, these fluorescence emissions exhibit a conical shape, following the spatial distribution of electrons, and the diameter of this conical fluorescence beam, best represented by the strongest emissions from $2PN_2$, is approximately 4 cm. We note that the morphological features of these optical emissions, including the conical shape and the size of the illuminated region, are in excellent agreement with experimental observations [13].

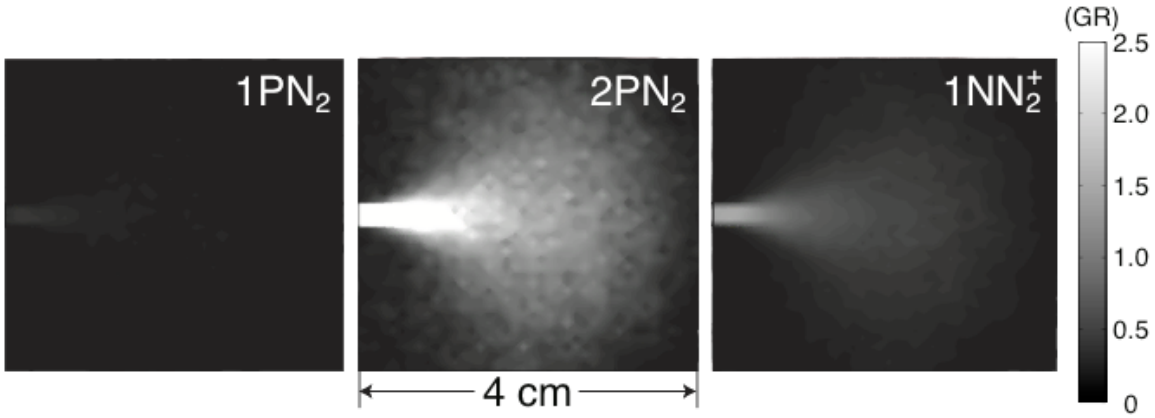

Figure 1. Simulation results of fluorescence radiation from air at ground pressure excited by a continuous beam of 50 keV electrons. Fluorescence emissions exhibit a conical shape. The diameter of this fluorescence beam, best represented by strongest emissions from $2PN_2$, is approximately 4 cm.

4. Optical Emissions Associated with TGFs

The main energy loss for runaway electrons occurs through ionization collisions with air molecules, resulting in low energy secondary electrons. These primary and secondary electrons are able to generate excited species via impact excitation, and fluorescence photons may be emitted by the radiative relaxation of these excited species. The characteristics of optical emissions that can be possibly generated in TGFs, including intensity and intensity ratios between optical band systems, mostly depend on the number density and energy distributions of electrons. Figure 2a shows the distribution of electrons, from sub-eV to a few tens of MeV, produced by the acceleration and multiplication of relativistic runaway electrons in a large-scale homogeneous reduced electric field of E/N = 70 Td (~18.8 kV/cm at $N = 2.688\times10^{25}$ m^{-3}). Figure 2b shows the same quantity, but obtained in the acceleration of thermal runaway electrons under the highly inhomogeneous electric field produced by a 100 MV lightning leader. The difference in electron energy distributions produced by the two production mechanisms, as observed in Figure 2b, is caused by the differences in geometry and magnitude between the homogeneous and inhomogeneous electric fields.

Different driving electric fields can lead to different acceleration and multiplication processes undergone by electrons, different energy distributions obtained, and thus different capabilities in generating optical emissions. In RREA mechanism, relativistic runaway electrons slowly get energy from the homogeneous electric field and gradually build up a 7.3 MeV high-energy cutoff while giving birth to a large ensemble of low energy electrons. Reciprocally, as demonstrated in [8], the intense inhomogeneous electric field naturally present in compact regions around negative lightning leader tips during stepping processes can accelerate thermal runaway electrons to high energy over a much shorter distance, corresponding to much less low energy electrons generated and a significantly different high-energy cutoff. A direct consequence of these differences is that the optical emissions associated with these two mechanisms are intrinsically different.

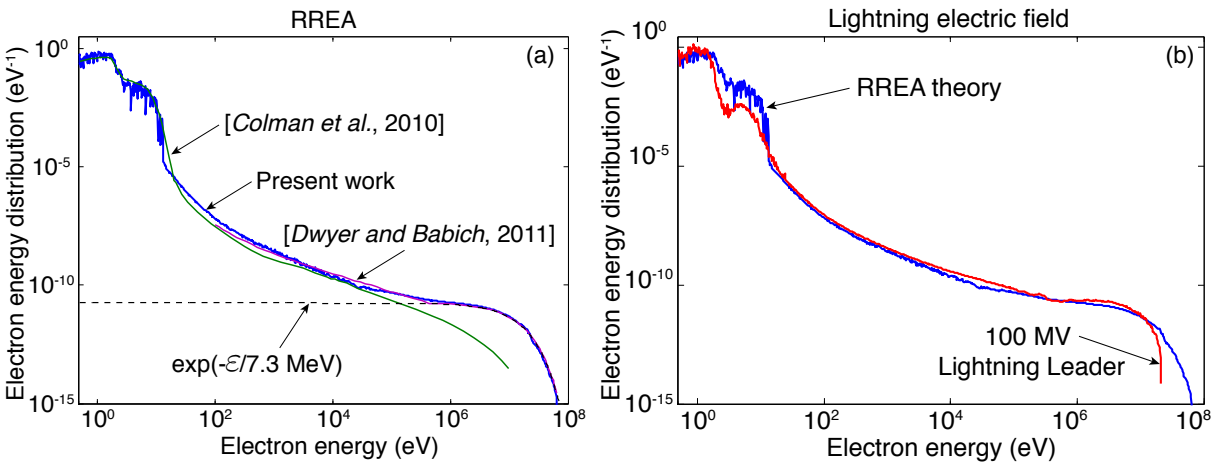

Figure 2. Distribution of electrons in the full energy range produced by the acceleration and multiplication of (a) relativistic runaway electrons in a large-scale homogeneous electric field of 70 Td and (b) thermal runaway electrons in the compact inhomogeneous electric field around the tip region of a 100 MV lightning leader. Also presented are electron energy distributions calculated for RREA processes documented in [14, 15].

Table 1 shows modeling results of optical emissions in the visible range with wavelengths between 390 nm and 700 nm produced by one of the following processes: RREA, acceleration of thermal runaway electrons in lightning leader field, and conventional streamer discharge. It is found that TGFs are most likely accompanied with detectable amount of optical emissions for both existing models. Moreover, since thermal runaway electrons gain energy over a much shorter distance from the lightning leader fields, optical emissions generated in this scenario are stronger. Intensity ratios between optical band systems are also different between the three processes, which primarily comes from the inherent differences in electron energy distributions.

Table 1. Optical emissions in Rayleighs in the visible range with wavelength between 390 nm and 700 nm

	Radius (m)	$1PN_2$ (R)	$2PN_2$ (R)	$1NN_2^+$ (R)	Intensity ratio $1PN_2/1NN_2^+$	Intensity ratio $2PN_2/1NN_2^+$
RREA (E = 70 Td)	1000	2.67×10^9	6.01×10^9	1.96×10^9	1.36	3.07
Thermal runaway electrons	50	8.91×10^{10}	9.37×10^{11}	8.32×10^{11}	0.11	1.13
Streamer Zone	40	9.76×10^9	6.83×10^{10}	6.75×10^8	14.46	101.19

5. Conclusions

Using a full energy range relativistic Monte Carlo model, we have quantified the optical emissions from $1PN_2$, $2PN_2$, and $1NN_2^+$ band systems that are generated during TGFs. The observation of optical emission, appearing as the low-energy signature of the underlying acceleration mechanism of high-energy electrons in TGFs, can be compared to the simulation results presented in this work in order to discriminate between the different TGF production mechanisms.

6. Acknowledgments

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