Properties of the thundercloud discharges responsible for terrestrial gamma-ray flashes

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1. Introduction

[2] Terrestrial gamma-ray flashes (TGFs) are intense bursts of gamma rays that originate from thunderstorms [Fishman et al., 1994]. They have durations ranging from a few tens of microseconds to a few milliseconds [Fishman et al., 2011; Briggs et al., 2013] and produce the highest energy emission of natural phenomena originating from within the Earth’s atmosphere, with particle energies typically reaching several tens of MeV [Dwyer and Smith, 2005; Tavani et al., 2011; Dwyer et al., 2012]. TGFs are relatively common, with a thousand or more produced around the planet each day [Østgaard et al., 2012; Briggs et al., 2013]. Paradoxically, even though they originate from deep within the atmosphere, at altitudes where aircraft routinely fly, the vast majority of TGFs that have been recorded so far were almost all observed by spacecraft in low Earth orbit, starting with the Compton Gamma-Ray Observatory in the early 1990s [Fishman et al., 1994], followed by observations by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [Smith et al., 2005; Grefenstette et al., 2009; Gjesteland et al., 2012], Fermi [Briggs et al., 2010, 2013], and AGILE spacecraft [Marisaldi et al., 2010a, 2010b; Tavani et al., 2011].

[3] TGFs have been shown to be associated with the initial stage of moderately strong positive intracloud (+IC) lightning [Cummer et al., 2005; Williams et al., 2006; Stanley et al., 2006; Lu et al., 2010; Shao et al., 2010; Cummer et al., 2011; Østgaard et al., 2013], presumably during the time when the negative leader is in the process of bridging the gap between the negative and positive charge regions inside the thundercloud.

[4] Spacecraft measurements, along with modeling of the propagation of the gamma rays up and out of the atmosphere, have found that the source altitudes of the gamma rays must be below about 20 km [Dwyer and Smith, 2005; Carlson et al., 2007; Gjesteland et al., 2010; Xu et al., 2012], within the altitude range of thunderstorms. The spectra of TGFs (up to a few tens of MeV) are consistent with bremsstrahlung emissions from energetic electrons accelerated by strong electric fields within the thunderclouds [Dwyer and Smith, 2005; Carlson et al., 2007; Xu et al., 2012], although there is currently some debate about the spectra at very high energies (~40–100 MeV) [Tavani et al., 2011; Celestin et al., 2012]. Calculations based upon RHESSI observations show that at the source, for each recorded TGF, the thunderstorm must have produced about 10^{12} high-energy electrons (average energy is 7 MeV), in order to account for the fluence of gamma rays recorded at the spacecraft many hundreds of kilometers away, although it is possible that some observed TGFs occur deeper in the atmosphere, requiring more high-energy electrons at the source (see example in section 4 below) [Dwyer and Cummer, 2013].

[5] It is a challenge to develop models that can explain how large numbers of high-energy electrons are generated so rapidly deep within the atmosphere [Dwyer, 2008]. In recent years, two main explanations have emerged: One involves ordinary lightning, and the other involves an exotic kind of discharge generated by X-rays and high-energy positrons. In this paper, we shall review these models and show that the latter generates lightning-like electric currents while producing little visible emission.

2. Runaway Electron Physics

[6] To understand the underlying mechanism for producing high-energy electrons in air and their accompanying X-ray and gamma-ray emissions, the rate that electrons lose energy while traveling through air must be considered. The energy loss per unit length, predominantly from ionization (solid curve) and bremsstrahlung losses (dashed curve), is
plotted in Figure 1 versus the kinetic energy of the energetic electron (or positron). When a moderately strong electric field is applied (e.g., Figure 1, horizontal line), for energetic particles with kinetic energies below \( e_{th} \), the rate of energy loss is greater than the rate of energy gain, causing the electrons to decelerate and stop. However, above \( e_{th} \), the electrons will gain more energy from the field than they lose to the air. These are the so-called runaway electrons, first described in Wilson [1925]. Monte Carlo simulations have shown that the minimum electric field required for electrons to run away and propagate long distances is \( E_{th} = 2.8 \times 10^6 \text{ V/m} \times n \) [Dwyer, 2003; Babich et al., 2004], where \( n \) is the density of air relative to that at sea level at standard conditions. This is slightly higher than the so-called breakeven field, \( E_{th} \), which corresponds to the minimum of the curve in Figure 1. At a very large field, \( E \sim 3 \times 10^7 \text{ V/m} \times n \), virtually all free electrons may gain energy and run away [Gurevich, 1961; Moss et al., 2006]. This “thermal runaway” mechanism, operating in the high fields associated with lightning leaders and streamer tips, is thought to be responsible for the X-ray emissions observed from lightning near the ground [Moore et al., 2001; Dwyer et al., 2003; Dwyer, 2004; Moss et al., 2006]. As will be discussed below, this mechanism has also been proposed as an explanation for TGFs [Dwyer, 2008; Celestin and Pasko, 2011; Celestin et al., 2012].

As energetic electrons ionize the air, some of the secondary electrons can be energetic enough to also run away. These secondary electrons will gain energy and generate additional electrons that will run away and so on. The result is an avalanche of energetic runaway electrons that grows exponentially with time and distance. This mechanism, which was first described by Gurevich et al. [1992], is commonly called the relativistic runaway electron avalanche (RREA) mechanism and has been investigated in many papers [e.g., Symbalisty et al., 1998; Lehtinen et al., 1999; Gurevich and Zybin, 2001; Dwyer, 2003; Babich et al., 2004, 2005; Coleman and Dwyer, 2006; Rouselle-Dupré et al., 2008; Celestin and Pasko, 2010; Dwyer, 2010; Dwyer and Babich, 2011; Babich and Bochkov, 2011]. Such an avalanche can be seen in Figure 2, which shows the results of a detailed Monte Carlo simulation. Hard scattering events, either Møller scattering (electron-electron elastic scattering) or bremsstrahlung, can be seen as sudden drops in the energy in the individual electron trajectories (black).

Figure 1. Energy loss per unit length experienced by a free electron (or positron) moving through air at STP as a function of kinetic energy. Figure from Dwyer [2004].

Figure 2. Monte Carlo simulation of (black) electrons and (blue) positrons moving through air at STP for an electric field strength of 1000 kV/m.
electric fields that may appear above thunderclouds after IC or cloud-to-ground (CG) lightning [e.g., Lehtinen et al., 1999; Gurevich and Zybin, 2001; Babich et al., 2008a, 2008b]. Because TGFs are observed to occur during the initial stage of +IC lightning, before a large amount of charge is transferred within the cloud, these cosmic ray models do not appear to explain most TGFs (for more discussion on this topic, see Dwyer [2008]).

[10] In contrast, lightning leader models are based upon the observations that negative lightning leaders emit hard (hundreds of keV) X-rays as they approach the ground [Dwyer et al., 2004], possibly caused by thermal runaway electron production [Dwyer, 2004; Moss et al., 2006]. Because the potential difference available to the runaway electrons near the ground apparently never reaches the tens of megavolts needed to generate RREAs, the resulting X-ray energy spectra are much softer than TGFs [Saleh et al., 2009; Schaal et al., 2012]. However, it has been conjectured that for lightning leaders within thunderclouds, the potential differences available to the runaway electrons in front of the lightning leaders could be much larger than near the ground, perhaps large enough to produce a TGF [Dwyer, 2008]. Calculations based upon the production rate of runaway electrons from lightning near the ground and reasonable assumptions about thunderstorm electric fields show that this mechanism could account for the number of gamma rays in a TGF [Dwyer, 2008; Saleh et al., 2009; Dwyer et al., 2010; Dwyer et al., 2012]. On the other hand, it is unclear if this mechanism is consistent with the radio emissions observed in association with TGFs [Dwyer and Cummer, 2013], and so, more work is needed on this topic. Several papers have modeled various aspects of the lightning leader mechanism, especially with the scenario that the runaway electron’s energy gain occurs primarily in the electric fields generated by the lightning leaders [Gurevich et al., 2007; Carlson et al., 2009, 2010; Celestin and Pasko, 2011; Celestin et al., 2012; Mallios et al., 2013].

[11] Figure 3 shows TGF model results for thermal runaway electron emission from lightning leaders inside thunderstorms as calculated by Xu et al. [2012], plotted with TGF data measured by RHESSI. The RHESSI data are the average spectrum for many TGFs, recorded with a range of spacecraft positions relative to TGF source location [Dwyer and Smith, 2005; Xu et al., 2012]. Two different thunderstorm potential differences are shown (red and dashed green curves), along with the results for the standard RREA calculation (black curve). As can be seen, the three curves and the data all agree at low energies. However, at high energies (e.g., >10^7 eV), the spectrum predicted by the lightning leader model with a 100 MV thundercloud potential (red curve) rolls over much quicker than the TGF data. Better agreement is achieved with the 200 MV thundercloud potential difference (dashed green curve), but the RREA model gives the best fit to the RHESSI TGF data. At even larger potentials, the lightning leader model will produce the same spectrum as the RREA model since the runaway electrons created by the lightning leader will undergo a large amount of additional RREA multiplication. The X-ray emission from lightning seen near the ground, which rarely extends beyond a few MeV, is an extreme example of the soft spectra that can be generated by lightning leaders when only small potential differences are present. In contrast, the fact that the RHESSI data match the RREA spectrum shows that rather large potential differences must be involved in the production of TGFs, with several RREA avalanche lengths present.

[12] Alternatively, the RFD model of TGFs assumes that a self-sustaining relativistic feedback discharge is created in the large-scale electric field region inside the thundercloud. This model also involves large electric potentials with several RREA avalanche lengths and so also produces a RREA energy spectrum (black curve) consistent with the RHESSI data, as seen in Figure 3.

[13] According to the RFD model, as a thundercloud charges, the amount of runaway electron avalanche multiplication may increase until the system approaches the self-sustaining feedback threshold. Once the feedback threshold is crossed, the electric current produced by the runaway electrons grows very rapidly, partially discharging that region of the storm [Dwyer, 2012; Liu and Dwyer, 2013]. One possible mechanism for rapidly pushing the system above the feedback threshold is for +IC lightning to discharge part of the avalanche region, enhancing the field in the remaining part. Detailed, self-consistent simulations show that when a thundercloud and IC lightning are modeled in this way, a large RFD occurs, which naturally has many of the same properties as TGFs, including similar time structures, gamma-ray fluences, RF emissions, and association with +IC lightning. A prediction of the RFD model is that large current-moment pulses (many tens of kiloamperes-kilometer) are generated by the runaway electrons and their accompanying ionization, which track the time profile of the gamma-ray emission [Dwyer and Cummer, 2013].

[14] These large current-moment pulses, in turn, produce strong radio pulses in the LF-VLF range, which have been measured. The connection between TGFs and large radio pulses has been known for many years, but the radio pulses were previously interpreted as resulting from normal lightning discharges closely associated with the TGFs [Inan

![Figure 3. Average energy spectrum of TGFs as measured by the (circles) RHESSI spacecraft along with (solid and dashed lines) model fits. The inset shows the dependence of the spectra on source altitude. The RFD model will produce the same energy spectrum as the RREA model and so also agrees with the RHESSI TGF data. Figure courtesy of Xu et al. [2012].](image)
et al., 1996, 2006; Cohen et al., 2006, 2010; Lu et al., 2011; Connaughton et al., 2010]. In fact, it is possible that many of these radio pulses associated with TGFs were not actually from normal lightning. Instead, it now appears that many of these observations may have been measuring the currents produced by the TGFs directly [Cummer et al., 2011; Connaughton et al., 2013; Østgaard et al., 2013].

4. Optical Emissions

[15] As discussed in section 3, it is possible that some or all TGFs are produced by thermal runaway electron production in association with lightning leaders. In that case, these TGFs are closely connected to specific lightning processes and may be viewed as a by-product of lightning. However, because we do not yet know what the specific lightning processes are, it is difficult to calculate the optical emissions associated with these TGFs, as there may be substantial lightning leader and streamer components. In this section, we shall instead calculate the optical emissions produced by relativistic feedback discharges, which are at least partially decoupled from the lightning processes within the thundercloud.

[16] In addition to TGFs, early studies have attempted to model transient luminous events (such as blue jets, gigantic jets, and red sprites) by calculating the optical emissions from RREAs above thunderstorms [Lehtinen et al., 1999; Babich et al., 2008c, 2008d]. RFDs also involve RREAs, although they are created by a different mechanism and occur in a different environment than in the previous studies. Unlike normal lightning, the RFD does not produce hot channels; therefore, there is no bright incandescent light. The main mechanisms for producing light by RFDs are the fluorescence from runaway electrons and excitation of neutral molecules by low-energy electrons generated by the RFD. To calculate the fluorescence emission intensity, we apply an approach that has been used to study the fluorescence emission from extensive air showers [e.g., Keilhauer et al., 2006]. The main fluorescence emission consists of two emission band systems: 2PN$_2$ and 1NN$_2$. Their spectra are dominated by strong blue and UV lines. However, instead of using band-resolved Einstein coefficients and deactivation constants [Keilhauer et al., 2006], we use the lumped values for each band system, as was done previously for modeling the optical emission of conventional streamers [Liu et al., 2006, 2009]. With this approach, our calculations show that the fluorescence yield in the wavelength between 300 and 400 nm produced by a minimum ionizing 0.85 MeV electron in air is 1.9–2.4 photons/m near the ground, which agrees with 2.5–4 photons/m calculated by Keilhauer et al. [2006] and 4 photons/m in the wavelength range between 300 and 430 nm measured by Lefeuvre et al. [2007]. These values change only slightly with altitude below 20 km.

[17] Here we focus on calculating the intensity of the emission produced by RFDs in the visible range of 390–700 nm. The volume emission rate in this wavelength range can also be calculated with the approach used by Keilhauer et al. [2006]:

$$E_{\text{opt}} = \frac{\sum e_0^\beta}{1 + \frac{2}{c \tau}} [F_{\rho n_{\text{ev}}} v(f(p) n_{\text{ev}}, f(p)) = \frac{1}{p \tau + p_0}. \quad (1)$$

The quantity $\sum e_0^\beta$ is the total fluorescence efficiency in the visible spectrum without quenching, and its values for 2PN$_2$ and 1NN$_2$ are about 0.0312% and 0.46%, respectively, which are obtained by combining measurements of the fluorescence efficiency for 0-0 bands of 2PN$_2$ and 1NN$_2$ [Keilhauer et al., 2006] and the spectra derived from aurora measurements [Valance-Jones, 1974]. The efficiency is reduced by a factor of $1 + \frac{2}{c \tau}$ at pressure $p$, where $\tau_0$ is the inverse of the Einstein coefficient, and $\tau_0$ is the inverse of the collisional quenching frequency. The term $F_{\rho n_{\text{ev}}}$ is the total energy deposited per unit volume per unit time by runaway electrons. The friction force $F_{\rho} = e E_{\rho}\xi$, where $e$ is the elementary charge, $E_{\rho} = 2.76 \times 10^5 \text{ V/m [Dwyer, 2012]}$, and $n$ is the density of air with respect to its value at sea level. The symbol $n_{\text{ev}}$ is the runaway electron number density, and $v$ is the average speed of runaway electrons. The function $f(p)$ characterizes the dependence of $E_{\text{opt}}$ on the pressure, where $p_0$ is the pressure where $\tau_0 = \tau_0$. The quenching altitudes of 2PN$_2$ and 1NN$_2$ are about 30 and 48 km, respectively, which are lower than 53 km for 1PN$_2$ [Liu et al., 2006, 2009], so that the 1PN$_2$ emission intensity is negligible for the fluorescence emission. At thundercloud altitudes, the distribution of the fluorescence emission intensity follows that of the runaway electron density.

[18] In addition to the fluorescence emission from runaway electrons, low-energy electrons created by the RFD can also excite N$_2$ molecules through collisions. At thundercloud altitudes, the lifetimes of the upper excited states of 1PN$_2$, 2PN$_2$, and 1NN$_2$ are very short, with the longest being those of 1PN$_2$, a few tens of nanoseconds. Steady state solutions of the model discussed in Liu and Pasko [2004] can be used to find the emission intensity due to low-energy electrons.

[19] Figure 4 shows the optical emissions from an RFD producing a single-pulse TGF, which was studied in detail previously [Dwyer, 2012; Liu and Dwyer, 2013]. The RFD is driven by an upward propagating +IC lightning discharge initiated at 0 ms between the lower negative and upper positive thundercloud charge layers ($Q \approx \pm 36.5C$) centered at 10 and 15 km, respectively. The RFD becomes self-sustaining at 0.36 ms and reaches its peak around 0.6–0.65 ms, and it is quenched by the subsequent self-produced ionization. Even though the RFD is initiated by lightning in this case, it may be viewed as a discharge path that is distinct from the lightning. At $t = 0.65$ ms, the runaway electron density has a maximum value of $9 \times 10^6 \text{ m}^{-3}$ at an altitude of 14 km. The horizontal radius of the RFD discharge is about 500 m, and the ratio $\frac{\theta}{R}$ is about 12 and 86 for 2PN$_2$ and 1NN$_2$, respectively. The results shown in Figure 4 can be verified by using those numbers and equation (1). The gamma-ray pulse shape, width, and magnitude shown in Figure 4a agree with a typical TGF observed by Fermi [Briggs et al., 2010; Fishman et al., 2011].

[20] The volume integrated optical intensity pulses (Figures 4b–4d) coincide with the TGF pulse produced by the RFD. Figures 4b and 4c show the intensities of the fluorescence emission generated by the runaway electrons, and Figure 4d shows the optical emission intensity of 1PN$_2$ due to the low-energy electrons, assuming that an average wavelength of 1PN$_2$ photons in the visible spectrum is 650 nm. The low-energy electrons do not have sufficient energy to produce 2PN$_2$ and 1NN$_2$. The intensity pulse in Figure 4d is about 3 orders of magnitude smaller than those in Figures 4b and 4c. As a result, the RFD is purplish blue.
The total optical energy radiated is approximately 40 J, which is many orders of magnitude smaller than that of normal lightning [Uman, 2001]. Therefore, the RFD is relatively dark compared to normal lightning. Although there may be lightning activity in parts of the thundercloud at the time of the RFD, which may produce some amount of visible light, unlike normal lightning, the RFD would produce a very large current pulse [Liu and Dwyer, 2013] that would not be accompanied by significant visible light emission. Østgaard et al. [2013] reported space-based optical measurements at the time of a TGF and found that detectable optical emission occurred after but not during the TGF, suggesting that the processes that generate the gamma rays do not simultaneously produce bright optical emission.

Figure 4e shows the total intensity distribution from all three emission band systems in rayleighs, assuming that the average wavelength of the 2PN$_2$ and 1NN$_2^+$ photons is 400 nm. The distribution is similar to that of the runaway electron density [see Liu and Dwyer, 2013, Figure 3], and the size of the luminous region is about 1 km across. The intensity is about an order of magnitude higher than sprite streamer heads that have a much smaller size. Therefore, although weak, the optical emission of the RFD may be detectable, although further calculations on the propagation of the light through the cloud are needed [Koshak et al., 1994]. In addition, the 1NN$_2^+$ emission is stronger than 2PN$_2$, which is quite different from streamer discharges. At altitudes of 70–75 km, the 2PN$_2$ emission intensity of sprite streamers is about a factor of several tens larger than 1NN$_2^+$ [Liu et al., 2006, 2009]. This factor is even larger at thundercloud altitudes because the quenching altitude of 2PN$_2$ is much smaller. This means that the RFD emission may be effectively differentiated from the streamer discharge emission by considering the relative strength between these two emission band systems.

As a final example, a model fit of the radio measurements of a Fermi TGF recorded on 3 August 2010 shows that the sum of path lengths of all the runaway electrons in the thundercloud at 13 km is 3.9 × 10$^{20}$ m for that event [Dwyer and Cummer, 2013], about 1.75 larger than the average TGF, making it a particularly strong discharge. Indeed, from the RF data, the inferred current moment for the 3 August event was 90 kA-km with a peak current of roughly 160 kA, which is large even compared with typical lightning first return strokes. In the visible range, calculations find that the fluorescence yield per unit length traveled by each runaway electron is about 0.7 photons/m or about 3.5 × 10$^{-19}$ J/m, valid for all altitudes below about 20 km. Combining this fluorescence yield with the sum of runaway electron path lengths for this TGF gives a total emission of only 135 J in the visible range associated with this very large current pulse.

### Discussion

In this paper, we have discussed two main mechanisms for generating TGFs within thunderstorms. At this time, it is not clear which mechanism describes most TGFs, but both are extremely interesting: If TGFs are produced by lightning leader emissions, then spacecraft are directly observing lightning in gamma rays many hundreds of kilometers away, illustrating that we have much to learn about ordinary lightning. On the other hand, if TGFs are produced by relativistic feedback discharges, then this means that a new and different kind of electrical breakdown commonly occurs inside ordinary thunderstorms.

Following Uman [2001], lightning can be defined as a transient, high-current electric discharge with length scales generally measured in kilometers. RFDs are also transient, high-current electric discharges with length scales measured in kilometers. In particular, RFDs produce large, lightning-like current pulses that generate radio emissions similar to lightning, causing lightning detection networks such as the World Wide Lightning Location Network (WWLLN) to identify the sources of these signals as lightning. However,
These discharges involve a novel mechanism of air breakdown that produces little visible light compared with normal lightning and so would appear dark to the human eye. The Townsend discharge, which is the low-energy analog of the relativistic feedback discharge, is sometimes called a dark discharge. Therefore, relativistic feedback discharges may be viewed as a kind of "dark lightning," with TGFs being one possible by-product.

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References


