

Source altitudes of terrestrial gamma-ray flashes produced by lightning leaders

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[1] Terrestrial gamma-ray flashes (TGFs) are energetic photon bursts observed from satellites and associated with lightning activity. Comparison between calculations based on the model of relativistic runaway electron avalanches (RREA) in large-scale weak electric field in thunderstorms and satellite measurements usually shows that the photon spectrum is consistent with source altitudes around 15 km. However, recent observations have located intra-cloud lightning (IC) discharges responsible for TGFs much deeper in the atmosphere (at altitudes ~ 10 km). In the present work, we show that the TGF spectrum as produced by acceleration of electrons in the strong electric field of stepping IC leaders is consistent with the lower altitudes recently discovered. This study reconciles observations and measurements by setting new altitudes for the TGF sources based on mechanism of direct acceleration of electrons in the lightning leader field. Moreover, the photon source beaming geometry is consistently determined from the geometry of electric field lines produced by the lightning leader. **Citation:** Xu, W., S. Celestin, and V. P. Pasko (2012), Source altitudes of terrestrial gamma-ray flashes produced by lightning leaders, *Geophys. Res. Lett.*, 39, L08801, doi:10.1029/2012GL051351.

1. Introduction

[2] Terrestrial gamma-ray flashes (TGFs) are high-energy photon bursts originating from the Earth's atmosphere. This brief ($\lesssim 1$ ms) natural high-energy phenomenon was first discovered in 1994 by *Fishman et al.* [1994] using the Burst and Transient Source Experiment (BATSE) detector aboard the Compton Gamma-Ray Observatory. Since then, TGFs have been observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [*Smith et al.*, 2005], the Fermi Gamma-Ray Space Telescope [*Briggs et al.*, 2010], and the Astrorivelatore Gamma a Immagini Leggero (AGILE) satellite, which recently measured the TGF spectrum up to 100 MeV [*Marisaldi et al.*, 2010; *Tavani et al.*, 2011].

[3] Although numerous TGFs have been observed [e.g., *Fishman et al.*, 1994; *Smith et al.*, 2005; *Grefenstette et al.*, 2009; *Briggs et al.*, 2010; *Marisaldi et al.*, 2010] and various models have been developed [e.g., *Dwyer and Smith*, 2005; *Carlson et al.*, 2007; *Østgaard et al.*, 2008], the production mechanisms of TGFs are still uncertain. TGFs are associated with thunderstorm activity and originate from bremsstrahlung emission by energetic electrons [*Fishman et al.*, 1994].

Although relativistic runaway electron avalanches (RREAs) theory [*Gurevich et al.*, 1992] has provided a very good agreement with satellite observations [*Dwyer and Smith*, 2005], it is now challenged by the recent measurements of the high energy part (>30 MeV) of the TGF spectrum measured by AGILE [*Tavani et al.*, 2011]. Moreover, observations have shown that TGFs are closely related to intracloud lightning transporting negative charges upward (+IC) [e.g., *Stanley et al.*, 2006; *Shao et al.*, 2010; *Lu et al.*, 2010, 2011; *Cummer et al.*, 2011] as predicted by *Williams et al.* [2006]. Based on theoretical grounds, it has been suggested that long unbranched +IC lightning leaders could produce a sufficient number of energetic electrons to explain TGFs without invoking further amplification in RREAs [*Celestin and Pasko*, 2011].

[4] In this paper, we determine the TGF source altitude using the combined RHESSI TGF spectrum by simulating the transport of photons produced by energetic electrons generated during the stepping of a high-potential lightning leader.

2. Model Formulation

[5] We calculate the electric field produced by the lightning leader during the stepping process using the method of moments. Then, we use a Monte Carlo model to simulate the acceleration of runaway electrons in this electric field. From the knowledge of the electron energy and momentum distribution functions, we generate the related bremsstrahlung photons and transport them through the atmosphere up to low-orbit satellite altitudes. In the following, we describe the numerical models used in this paper.

[6] We use the method of moments [*Balanis*, 1989, p. 670] in order to calculate the electric field in the vicinity of a +IC lightning negative leader tip during the corona flash associated with the stepping of the leader (see *Celestin and Pasko* [2011, and references therein] for discussion of related phenomenology). The electric potential of the lightning leader tip with respect to the ambient potential is approximately $V_0 = E_0 l / 2$ [*Bazelyan and Raizer*, 2000, p. 54], where l is the length of the unbranched leader channel. The ambient large-scale thunderstorm electric field is taken as $E_0 = 5 \times 10^4$ V/m [e.g., *Marshall et al.*, 2001]. The radius of the leader channel is chosen to be 1 cm [*Rakov and Uman*, 2003, section 4.4.6, p. 134], and the IC lightning length is $l = 4$ km. The latter parameter is chosen to provide a difference of 100 MV between the potential in the leader tip and the ambient potential. Note that this is 10 times the magnitude of the electric potential difference used by *Celestin and Pasko* [2011]. The electric potential difference is an important parameter as it defines the maximum energy that runaway electrons can gain from the leader field. Indeed, in our

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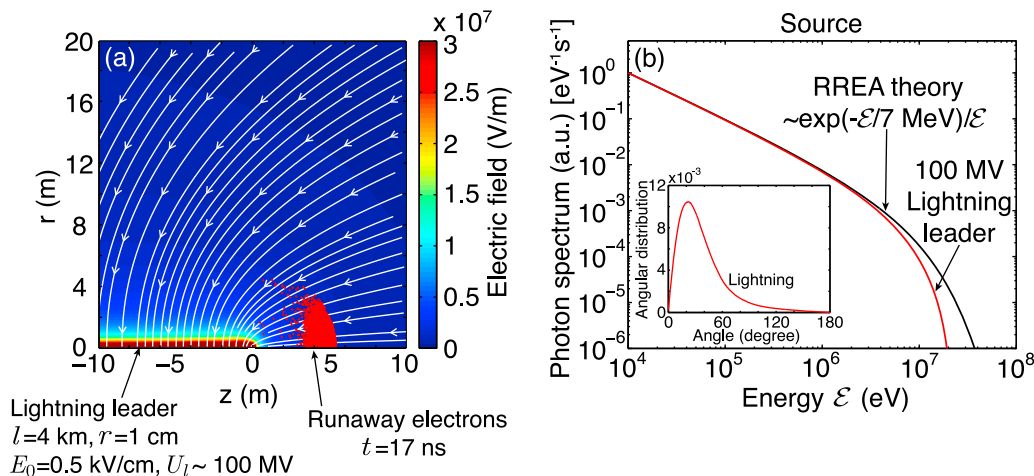


Figure 1. (a) Illustration of the electric field in the vicinity of a 100 MV lightning leader. Figure 1a also shows the positions of runaway electrons at $t=17$ ns obtained from our Monte Carlo model. (b) RREA and lightning bremsstrahlung photon spectra. The inset in Figure 1b shows the angular distribution of source photons produced by bremsstrahlung emission of energetic electrons accelerated in the lightning leader field.

simulations, we have observed that a 100 MV lightning leader produces electrons with a maximum energy of a few tens of MeVs, as typically observed in TGFs.

[7] In order to simulate the propagation and collisions of electrons in air under a given applied electric field, we use a Monte Carlo model, which 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 [Celestin and Pasko, 2010, 2011]. Bremsstrahlung radiation is simulated using an analytical bremsstrahlung differential cross section [Lehtinen, 2000, pp. 45–49]. In order to accelerate the electrons in the lightning leader field, we input the electric field obtained using the method of moments in the Monte Carlo code.

[8] Numerous streamers are produced during the stepping process of the negative leader. It has been shown that the runaway electrons emitted from negative streamers are able to gain energies as high as ~ 65 keV [Celestin and Pasko, 2011]. It is likely that streamers will interact with each other, however, the complexity of this problem prevents us from explicitly taking into account these interactions. Likewise, it is difficult to establish without additional dedicated studies if the streamer interactions will prevent (by shielding) or amplify the production of runaway electrons. Once injected in the leader tip region, we use our Monte Carlo model to simulate the further acceleration of these runaway electrons in the electric field produced by the lightning leader during the stepping process. It is important to note that in this work, we do not simulate the electric field produced during the stepping process of the lightning leader in a self-consistent fashion. In order to avoid accelerating the electrons in an unphysically high electric field, we set the initial location of electrons to 30 cm from the leader tip where the electric field is 200 kV/cm and should relax over a typical time of 0.3 ns [see Celestin and Pasko, 2011, Figure 7]. Note that this particular location has little effect on the final energy gained by the runaway electrons.

[9] The Monte Carlo model developed to simulate photon propagation through the atmosphere is similar to that described by Østgaard et al. [2008]. Photons with energies

from 10 keV to 100 MeV can be simulated. Three different photon collision types are considered: Photoelectric absorption (main process for energies up to ~ 30 keV), Compton scattering (main process from ~ 30 keV to ~ 30 MeV) and electron-positron pair production (main process >30 MeV). If the type of collision is photoelectric absorption, the photon is removed from the pool. If the type of collision is Compton scattering, the photon energy is changed according to this process [e.g., Lehtinen, 2000]. If the type of collision is electron-positron pair production, the positron is assumed to annihilate locally and two photons with energy of 511 keV in opposite directions are added to the pool of photons. The secondary Compton-produced electron bremsstrahlung is not taken into account. These simplifications are justified by the good agreement obtained with previously published results [e.g., Dwyer and Smith, 2005]. In this model, photons propagate in the atmosphere up to 500 km, that is the typical altitude of low-orbit satellites detecting TGFs. In order to calculate the TGF spectrum, the photons that escape the atmosphere are integrated over a nadir angle ranging from 0° to 45° . Additionally, the photon spectra are averaged over the distance from the subsatellite point.

3. Results

[10] TGF spectra depend on the electron energy distribution at the source, the electron beam geometry and the source altitude [Dwyer and Smith, 2005]. In this paper, electron energy distribution and the electron beam geometry are consistently obtained from the acceleration of electrons in the electric field of a stepping lightning leader.

[11] Figure 1a shows the electric field lines calculated by the method of moments and the acceleration of thermal runaway electrons [e.g., Celestin and Pasko, 2011] in the vicinity of the lightning leader tip. The time integrated (over 108 ns) photon spectra generated in the high-potential difference produced by the lightning leader and in the case of RREA theory using a 45° beaming angle are shown in Figure 1b. One sees that the photon spectrum produced by the thermal runaway electrons in the 100 MV lightning leader

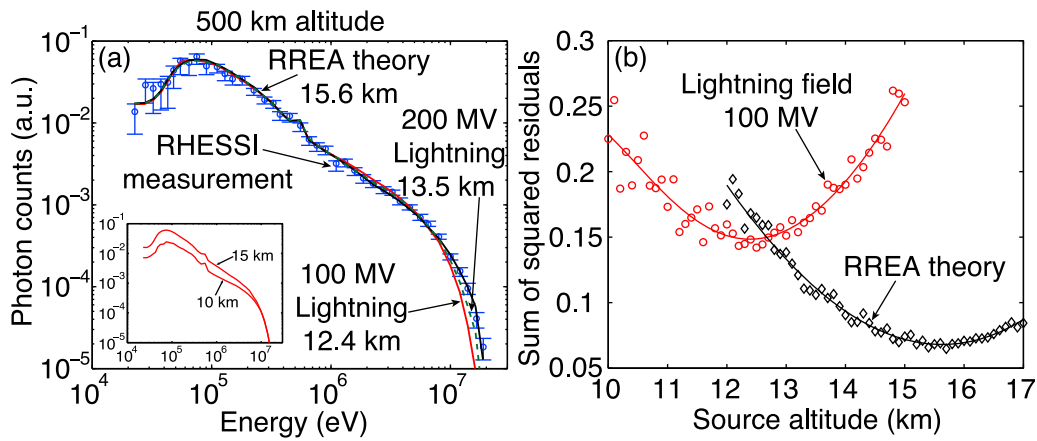


Figure 2. (a) Comparison between RHESSI measurements and simulated spectra. The source altitude of lightning-produced TGF is estimated from the low energy part of the spectra. An RREA source with 45° beaming angle at 15.6 km generates a spectrum consistent with RHESSI data. The spectrum produced by a 100 MV lightning leader matches RHESSI data for a source located at 12.4 km. The spectrum produced by a 200 MV lightning leader matches RHESSI data for a source located at 13.5 km (dashed line). The combined RHESSI data are obtained from *Dwyer and Smith* [2005]. The inset in Figure 2a illustrates the variations in lightning-produced TGF spectrum (100 MV) for source altitudes between 10 and 15 km. (b) Sum of squared residuals calculated between RHESSI data and simulated spectra of both mechanisms for an altitude range from 10 km to 17 km. Solid lines show third-degree polynomial fits to the data.

case is softer than that of the RREA theory that demonstrates the typical 7 MeV cutoff signature [e.g., *Dwyer*, 2008]. The inset in Figure 1b shows the angular distribution of the lightning-produced photon source with energy between 10 keV and 100 MeV.

[12] Figure 2a shows the simulated spectra corresponding to the two mechanisms with different source altitudes that give the best match with the combined RHESSI spectrum. Due to the limited spatial extent of the detector, the measured spectrum is different from the real photon spectrum. Indeed, some photons will partially release their energy in the detector, for example by Compton scattering, before exiting it. In order to compare directly our simulation results with RHESSI measurements, the detector response is taken into account by applying the RHESSI detector response matrix [*Dwyer and Smith*, 2005; *Grefenstette et al.*, 2009] (available at http://scipp.ucsc.edu/~dsmith/tgflib_public/data/).

[13] In this study, the simulation is conducted to model a TGF produced by one specific lightning discharge while RHESSI TGF spectrum is a spectrum accumulated over many TGF events. It is possible that the TGF spectrum generated by lightning discharge does not exactly match the averaged RHESSI data in the high energy part, which is established by the specific potential of the lightning event. It is important to note that for a higher potential lightning discharge of 200 MV, the related TGF spectrum is able to reproduce entirely the averaged RHESSI spectrum (see Figure 2a). However, for the purpose of determining source altitudes of TGFs, it is enough to observe the effects of atmospheric attenuation on the low energy part of the spectra. Indeed, high-energy photons have a reduced probability of collision, and the corresponding part of the photon spectrum directly depends on the available potential difference due to the lightning leader. Different electric potentials of lightning discharges produce different high energy parts of the spectrum, while the low energy part is mostly defined by the source altitude (see inset in Figure 2a). In this context, it seems that 100 MV lightning leaders are among the least

energetic discharges that could produce TGFs as observed by RHESSI. The transition point between low and high energy parts is approximately 10 MeV. The source altitude is estimated by matching the low energy part with the averaged RHESSI data.

[14] An RREA-produced TGF at 15.6 km altitude with a 45° beaming angle provides a spectrum consistent with RHESSI spectrum. This altitude is very close to that estimated by *Dwyer and Smith* [2005] and *Carlson et al.* [2007]. Figure 2a also shows that a high-potential lightning leader at 12.4 km altitude is able to explain the RHESSI TGF spectrum as well.

[15] The least square method is used to quantify the agreement between the simulated TGF spectra corresponding to different source altitudes and RHESSI data. Since the normalization of the spectrum is a free parameter, each point of Figure 2b corresponds to the normalization factor that provides the minimum of the sum of squared residuals for a given altitude. Using the photons produced by the electrons accelerated in the field produced by the stepping of the 100 MV +IC lightning leader, we find that a TGF source located at 12.4 km would give the best match to the RHESSI data. In the case of a 200 MV lightning leader, the best match is found for an altitude of 13.5 km.

4. Summary and Discussion

[16] In this work, we have simulated the dynamics of energetic electrons accelerated in the electric field produced during the stepping process of high-potential lightning leaders propagating upward [*Celestin and Pasko*, 2011]. Using the calculated geometry of this electron beam and the electron energy distribution function, we have simulated the production and transport of the corresponding bremsstrahlung photons through the atmosphere up to the TGF-detecting satellite altitude. From the calculation of the measured spectra and comparison with RHESSI data, we have determined a corresponding likely TGF source altitude of 12.4 km. In the

case of RREA, the simulation results from our model are consistent with previous works [e.g., *Dwyer and Smith*, 2005].

[17] The photon beam geometry is determined from the energy and beaming geometry of the source electrons. In the lightning leader case, these quantities directly follow from the layout of the electric field calculated using the method of moments. The momentum distribution of photons after their generation through bremsstrahlung collisions is calculated from the momentum distribution of electrons in our model. This consistent simulation of momentum distribution for both electrons and photons provides us with a direct quantitative description of the beaming geometry of the source photons without requirement of any additional assumptions. The momentum distribution of source photons with energies >10 keV is found to be a broad beam with an average angle of 37.7° (see inset in Figure 1b), in agreement with previously published results on the beaming of TGF sources [e.g., *Carlson et al.*, 2007; *Gjesteland et al.*, 2011]. Note that *Carlson et al.* [2009] had predicted that lightning discharges would naturally produce unbeamed photon sources.

[18] From the theory developed by *Celestin and Pasko* [2011], we can estimate that the 100 MV lightning leader used in this study produces $\sim 10^{18}$ energetic electrons. Using the simulation results obtained in the present study, we estimate that these electrons and the secondary energetic electrons generate $\sim 10^{19}$ energetic photons through bremsstrahlung emissions. At satellite altitude, we find a model calculated fluence of 3 photons/cm² at 200 km distance from the subsatellite point. We note that this value is obtained based on an order of magnitude estimate of the number of electrons produced during the stepping of a 100 MV lightning leader. The average RHESSI TGF fluence is 0.1 photons/cm² [*Smith et al.*, 2005]. According to *Gjesteland et al.* [2010], BATSE measured 0.3–0.6 counts/cm². Including calculations of dead time effects, *Briggs et al.* [2010] found that a typical bright TGF has a fluence of 0.7 photons/cm².

[19] As shown in Figure 1b, the source photon spectrum for the 100 MV lightning leader case is softer than that produced by RREA. This difference is due to the fact that the electric field driving runaway electrons has a limited spatial extent in the case of a stepping leader. Indeed, electrons can only gain part of the potential energy available and by the time they have stopped in the regions where electric field is too low to sustain their acceleration, the time averaged electron energy distribution appears to be not as energetic as in the RREA case (Figure 1b). We see that 100 MV lightning leaders should be among the least energetic discharges that could produce TGFs as observed by RHESSI. In fact, RREA-producing fields are extended over long enough distances to enable the distribution of electrons to reach the RREA steady state. In the same context, while lower potential lightning leaders would lead to too few energetic photons to be observed by a satellite, they would produce an even softer electron distribution than that obtained in the present paper. We conjecture that many more TGFs with lower energy and lower fluence are produced by lightning with lower potential. These are yet to be detected because of their low fluence. The related bremsstrahlung radiation manifests itself in X-ray bursts observed at close range from negative cloud-to-ground lightning discharges [e.g., *Moore et al.*, 2001; *Dwyer et al.*, 2005].

[20] At the source, the leader-produced photon spectrum has a lower high energy cutoff than that of the RREA

spectrum (Figure 1b). The source of photons needs to be placed at lower altitudes for the simulated spectrum to match RHESSI measurements. Indeed, the deeper in atmosphere a given source spectrum is placed, the harder is the observed spectrum at satellite altitude. The inset in Figure 2a illustrates this point by showing variation of lightning-produced TGF spectrum observed at satellite altitudes for source altitudes between 10 and 15 km. It is worth mentioning that a lightning source at 8 km is ruled out since the related spectrum is outside the error bars of the RHESSI measurements.

[21] We note that an altitude of 12.4 km (100 MV) or 13.5 km (200 MV) of the TGF source found in this study lie within the typical range of observations of TGF-producing +IC lightning. Indeed, recent studies of TGF-related lightning processes suggest that TGF sources are located at altitudes lower than originally thought. In fact, *Stanley et al.* [2006] found two specific TGF-related intracloud lightning discharges at 13.6 km and 11.5 km. Further study of TGF-related sferics by *Shao et al.* [2010] suggests a TGF source in the altitude range 10.5–14.1 km. *Lu et al.* [2010] also found that TGFs are produced during the initial development of intracloud lightning between a negative charge region centered at about 8.5 km and a positive region at 13 km altitude.

[22] It is also interesting to note that a 12.4 km TGF source altitude happens to be closer to the altitudes of commercial flights and a large amount of TGF electrons and photons in the source region may potentially lead to significant radiation doses received by aircraft passengers [*Dwyer et al.*, 2010]. However, we emphasize that in the proposed leader based model the electron beam does not extend over a large distance (few tens of meters), and further studies on the probability for an aircraft to be exposed to radiation from TGF sources need to be carried out.

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