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Key Points:
- Relativistic electrons are produced during the breakdown of ICs during a current surge when two streamer coronae approach each other
- The acceleration of electrons between two streamer coronae leads to TGFs lasting for tens to hundreds of μs with photon energies of $\mathcal{O}$(10 MeV)
- The maximum photon energy in TGFs is determined by the electric field of the upper cloud charge layer

Supporting Information:
- Supporting Information S1
- Data Set S1
- Text S1

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The Emission of Terrestrial Gamma Ray Flashes From Encountering Streamer Coronae Associated to the Breakdown of Lightning Leaders

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Abstract Terrestrial gamma ray flashes (TGFs) are beams of high-energy photons associated to lightning. These photons are the bremsstrahlung of energetic electrons whose origin is currently explained by two mechanisms: energizing electrons in weak, but large-scale thundercloud fields or the acceleration of low-energy electrons in strong, but localized fields of lightning leaders. Contemporary measurements by the Atmosphere-Space Interactions Monitor suggest that the production of TGFs is related to the leader step and associated streamer coronae when upward moving intracloud lightning illuminates. Based on these observations, we apply a particle-in-cell Monte Carlo code tracing electrons in the superposed electric field of two encountering streamer coronae and modeling the subsequent photon emission. We also perform a parameter study by solving the deterministic equations of motion for one electron. We find that this mechanism can explain the occurrence of TGFs with photons energies of several MeV lasting for tens to hundreds of μs, in agreement with observations.

Plain Language Summary For more than two decades, it has been known that thunderstorms emit high-energy X-rays and γ rays, the so-called terrestrial gamma ray flashes (TGFs) lasting for tens to hundreds of μs, which are the bremsstrahlung ("braking radiation") of energetic electrons and are the most energetic natural phenomena on Earth. Within the last years, two theories have been crystallized out to explain the origin of energetic electrons: the acceleration and multiplication of energetic electrons as remnants of cosmic rays in the large-scale electric fields of thunderclouds or the acceleration of thermal electrons in high electric fields in the vicinity of the tips of lightning leaders. Contemporary measurements of the Atmosphere-Space Interactions Monitor (ASIM) show that TGFs are produced at the onset of the main optical lightning pulse, indicating that the electron acceleration is related to the upward pointing lighting leader tip. We have performed computational simulations of the electron acceleration in the superposed electric field of two encountering streamer coronae, a compilation of small plasma channels with high-field tips, arising in the proximity of the lightning leader tip and the upper charge layer. We find that this scenario can explain the occurrence of TGFs with energies and durations compatible with previous and contemporary measurements.

1. Introduction

Terrestrial gamma ray flashes (TGFs) are bursts of energetic gamma rays with single photon energies of up to 40 MeV lasting for tens to hundreds of microseconds and are associated to the occurrence of lightning (Briggs et al., 2010; Fishman et al., 1994). They were first observed above thunderclouds by the Burst and Transient Source Experiment (BATSE) (Fishman et al., 1994), confirmed later by various other missions such as AGILE (Marisaldi et al., 2010; Tavani et al., 2011), Fermi (Briggs et al., 2010), RHESSI (Cummer et al., 2005; Smith et al., 2010), and GROWTH (Tsuchiya et al., 2011) and are subject to the current ASIM (Atmosphere-Space Interactions Monitor) (Neubert et al., 2019) and future TARANIS (Tool for the Analysis of Radiation from lightning and Sprites) (Blanc et al., 2007) missions with payloads dedicated to the measurement of lightning flashes and associated phenomena like transient luminous events (TLEs) and TGFs. In addition to these spaceborne measurements, ground-based measurements of rocket-triggered lightning and laboratory experiments have confirmed the emission of energetic radiation from electric discharges

(Babich et al., 1990; Babich & Loiko, 2009; Dwyer et al., 2005; Kochkin et al., 2016; Nguyen et al., 2010; Rahman et al., 2008; Schaal et al., 2012; Stankevich & Kalinin, 1967).

The payload of ASIM consists of two optical cameras and three photometers with bandwidths in 337 nm, associated to the emission in the second positive band of molecular nitrogen, thus revealing streamer activity, and in 777 nm, associated to the spectral emission from atomic oxygen, hence indicating the activity of the hot leader channel, as well as two X-ray and gamma ray detectors measuring the high-energy emission of TGFs (Chanrion et al., 2019; Neubert et al., 2019; Østgaard et al., 2019).

Whereas it is known that TGF photons are produced through energetic electrons through the bremsstrahlung process, it has been debated so far which exact mechanism in lightning discharges is responsible for the acceleration of electrons to relativistic energies. While electrons in air are accelerated in an ambient electric field and thus gain energy, they also lose energy through inelastic collisions with air molecules. The resulting friction force F_R, depending on the electron energy as well as collision and energy loss probabilities, confines the majority of electrons at that energy level where F_R equilibriates with the local electric force. Since electron-molecular collisions are stochastic processes, there is a small probability that electrons reach energies above this equilibrium energy. However, only if electrons reach energies larger than approximately 150–200 eV, where the friction force in air takes its maximum, does the further electron acceleration become systematic rather than stochastic leading to a significant multiplication of energetic electrons (Babich, 2005; Gurevich, 1961; Kunhardt et al., 1986; Wilson, 1925), named runaway electrons by Eddington (1926).

Hence, the question of the origin of TGFs is equivalent to the question of how to generate energetic electrons at time scales of microseconds. There are currently two theories explaining the seed population of relativistic electrons: the leader-streamer process in which low-energy electrons are accelerated in the high-field regions localized in the vicinity of lightning leader tips (Babich, 2003; Babich et al., 2011, 2013, 2015; Carlson et al., 2010; Celestin & Pasko, 2011; Dwyer et al., 2005; Köhn & Ebert, 2015; Köhn et al., 2017, 2020; Xu et al., 2012) or the continuous acceleration and multiplication of high-energy electrons as remnants of cosmic rays in the large-scale electric fields of thunderstorms (Babich et al., 2005; Dwyer, 2003, 2007, 2012; Gurevich et al., 1992; Gurevich & Zybin, 2001; Wilson, 1925). Since both mechanisms can explain the occurrence of energetic electrons and photons, their energy distributions as well as the beam duration, it has been undecided so far which mechanism really is responsible for the production of TGFs.

Now, with the recent measurements of ASIM, we are finally able to confine which of the two aforementioned scenarios might be the more likely one to generate TGFs. Here and in an accompanying publication in preparation, we present the simultaneous measurement of the X-ray and gamma ray detectors and the photometers suggesting the leader-streamer mechanism as the one producing TGFs where, in addition to the negative streamer corona in the vicinity of the leader tip, positive streamers are initiated from hydrometeors in proximity of the upper charge layer in the field of the approaching leader (Babich et al., 2016). Based on these measurements, we focus on modeling the TGF emission at their source location and investigate the production of energetic electrons and associated photon beams with a particle-in-cell Monte Carlo code. We perform a parameter study by solving deterministic, relativistic equations of motion including the electric fields of lightning leaders as well as of streamers and the friction force of electrons in air.

Based on ASIM measurements, we describe the suggested physics behind the production of TGFs and discuss the relative timing between the occurrence of TGFs and the associated main optical pulses as well as our model in section 2. We present the results of our simulations in section 3 and discuss the energy distributions of electrons and photons as well as the beam durations and conclude on the TGF producing mechanism in section 4.

2. Methodology and Model

2.1. Timing and Duration of TGFs Relative to the Main Optical Lightning Pulse

Figure 1a shows the irradiance of photons in the wavelength of 777 nm measured by ASIM and associated to lightning discharges and the occurrence of TGFs. Radiation in this wavelength is emitted by atomic oxygen produced by the hot lightning leaders. Thus, taking into account the delay of optical photons due to their scattering inside clouds (Light et al., 2001), these examples show that TGFs occur approximately at the onset of the main optical pulse associated to the subsequent electric breakdown (Neubert et al., 2020); note that

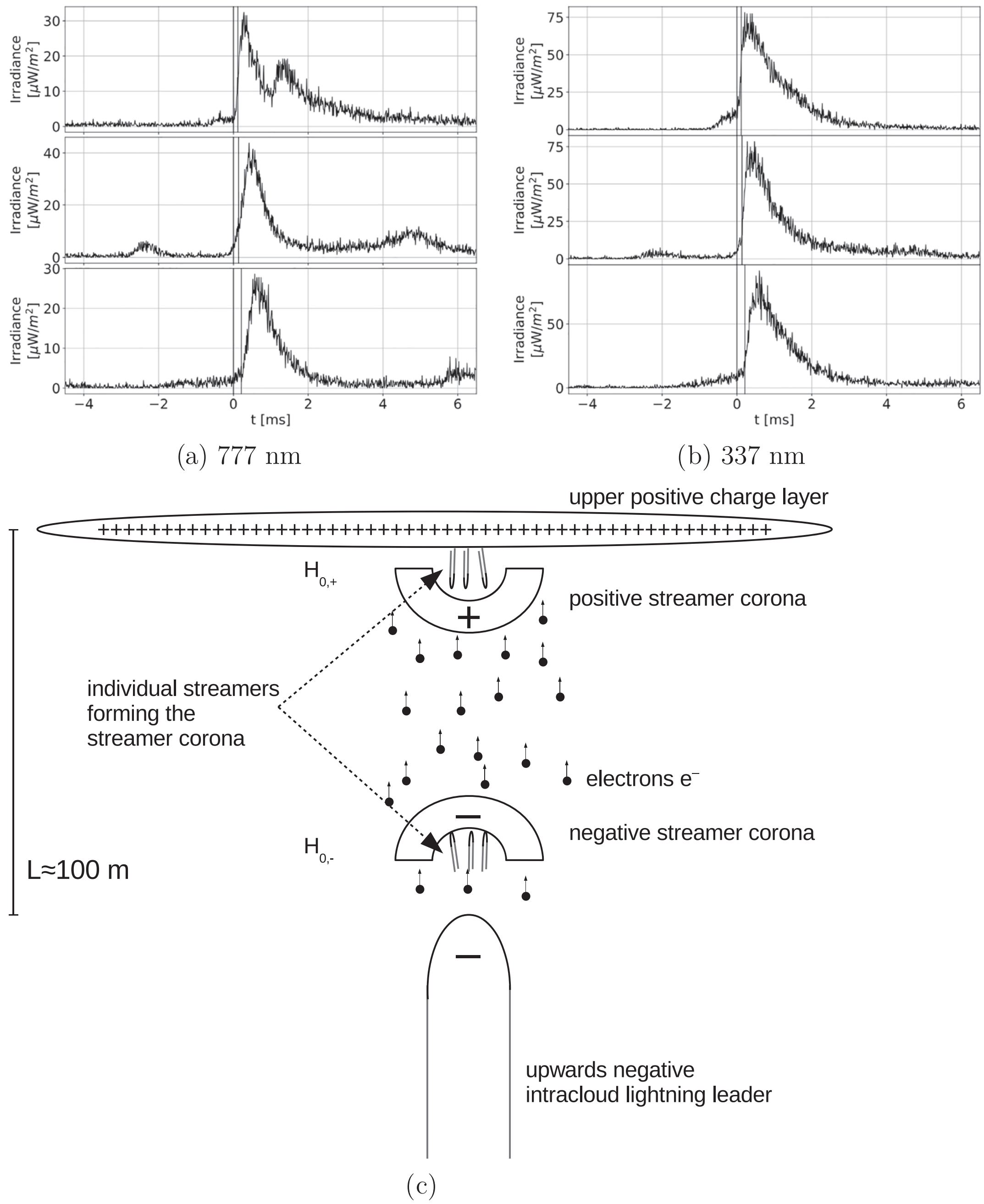

Figure 1. (a, b) The irradiance of photons with wavelengths of 777 (a) and 337 nm (b) of lightning discharges associated with TGFs as a function of time. The first solid line at $t = 0$ shows the TGF occurrence time; the second solid line shows the end time of the TGF. (c) Sketch of the TGF producing mechanism: During the leader step before optical emission, low-energy electrons move between the leader tip and the upper positive charge layer (arrows indicate the direction of electron drift). Subsequently, streamer coronae incept at the upper charge layer and in the vicinity of the leader tip, propagating toward each other and accelerating electrons into the runaway regime.

for events before March 2019, there is a $\pm 80\,\mu s$ uncertainty between MXGS and MMIA signals (Østgaard et al., 2019). We thus relate the occurrence of TGFs to a large current surge indicating a leader step with a characteristic length scale of $\sim$100 m (Berger, 1967; Chen et al., 1999; Lyu et al., 2016; Schonland, 1956). In addition to the ASIM measurements, various ground-based measurements of electromagnetic waves confirm the correlation between TGFs and lightning leaders (Cummer et al., 2011, 2015). Panel (b) shows the irradiance in the wavelength of 337 nm associated to the emission in the second positive band of molecular nitrogen pointing to the occurrence of streamers. Hence, panel (b) shows that the first TGF photons are produced shortly after the onset of streamer activity, adjacent to the stepping process before the leader reaches the upper positive charge layer in a cloud. Similarly, in laboratory discharge experiments, the emission of X-rays has been observed accompanied by streamer coronae (see, e.g., Kochkin et al., 2015, 2016); although the energies in laboratory discharges are smaller than in thunderstorm, this indicates that the emission of TGFs is attributed to streamer coronae rather than to individual streamers.

The overall physical scenario is sketched in Figure 1c: At the beginning of the leader step, electrons are constantly emitted from the leader tip and move toward the upper positive charge layer. Although the electric field at the tip could potentially exceed several times the classical breakdown field E_k (Köhn & Ebert, 2015; Skeltved et al., 2017; Xu et al., 2012), forthcoming streamers in the vicinity of the leader tip will shield the electric field down to a few E_k (Bazelyan & Raizer, 2000). Therefore, the leader field alone without taking the effect of associated streamer coronae into account is not capable of accelerating electrons to relativistic energies and during their motion to the upper charge layer, the friction force limits the electron energies to approximately 100–200 eV (Gurevich, 1961) equivalent to velocities of $\approx(6–8) \cdot 10^6$ m s^{-1}. Instead, the leader step is accompanied by streamer coronae such that the joint system of streamers and leaders accelerates electrons to relativistic energies (Moore et al., 2001). Assuming a length scale of 100 m for a leader step and thus for the gap between the leader tip and upper charge layer, this means that electrons need at least $\Delta t \gtrsim$ 12.5–16.67 μs before reaching the upper layer.

After sufficiently many electrons have crossed the gap between the leader tip and the upper charge layer, two streamer coronae form, one positive corona from hydrometeors assisted by the electrons in the vicinity of the layer (Babich et al., 2016) and moving downward from the upper charge layer, and one negative, upward propagating corona ahead of the leader tip. As we discuss below, electrons are subsequently accelerated in the superposed electric fields of the streamer coronae; hence, the minimum duration of TGFs is the time difference of the time $t_{runaway}$ when the first runaway electron appears between the two streamer coronae and their collision time t_{coll}. Finally, both coronae encounter and shorten the field, terminating the acceleration of electrons into the runaway regime.

2.2. Monte Carlo Simulations

We employ a 2.5-D particle-in-cell Monte Carlo code with two spatial coordinates $\mathbf{r} = (r, z)$ and three velocity coordinates $\mathbf{v} = (v_r, v_\theta, v_z)$ with cylindrical symmetry to simulate the motion of electrons at 10 km altitude, which is in the order of the production altitude of TGFs (Cummer et al., 2015; Dwyer & Smith, 2005; Østgaard et al., 2008; Stanley et al., 2006; Xu et al., 2012), as well as the emission and motion of energetic photons. We have implemented elastic scattering, excitations, impact ionization, and electron-nucleus and electron-electron bremsstrahlung (Bethe & Heitler, 1934; Chanrion & Neubert, 2008; Jacob, 1973; Köhn & Ebert, 2014; Köhn et al., 2014; Lawton & Phelps, 1978; Phelps & Pitchford, 1985; Yong-Kim & Santos, 2000) for electrons scattering off air molecules and photoionization, Compton scattering as well as positron and hadron production for photons (Fuller, 1985; Köhn & Ebert, 2014; Peskin & Schroeder, 1995). Since electrons ionize molecular nitrogen and oxygen, the electron number grows exponentially; due to limited computer memory, we use an adaptive particle scheme conserving the charge distribution as well as the electron momentum such that every simulated electron is actually a superelectron (Chanrion & Neubert, 2008; Köhn et al., 2017b).

Due to computer and runtime limitations, we choose a two-step approach where we trace low-energy electrons between the leader tip and the upper charge layer in the first step and secondly accelerate low-energy electrons to runaway energies and emit bremsstrahlung photons in the superposed electric field of the lightning leader and the two encountering streamer coronae, which incept after electrons have bridged the gap between the leader tip and the upper charge layer.

In the first step, we initiate a current of 1 kA (Gurevich et al., 2007; Uman, 2001) of electrons with an initial energy of $\approx$2 eV in a field of $5E_k$, 80 cm ahead of the leader tip, and trace them in the electric field (Köhn & Ebert, 2015) in an ambient field of $E_0 = 0.5$ kV cm$^{-1} \approx 0.05E_k$ only until they bridge the gap between the leader tip and the upper charge layer. During this first simulation step, we solve the Poisson equation $\Delta\Phi(\mathbf{r}) = e_0 \left(n_i(\mathbf{r}) - n_e(\mathbf{r})\right)/\varepsilon_0$ accounting for the different velocities of electrons with density n_e and ions with density n_i (Chanrion & Neubert, 2008). This first step is executed to determine the spatial and energy distribution of low-energy electrons used as an input for the second simulation step. Note that for fields $\lesssim 5E_k$, the actual initial field does not influence the electron energies significantly.

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In the second simulation step, we trace these low-energy electrons in the electric field superposed of the leader field and the field $E_{coro,\pm}$ of a positive (+) and negative (-) streamer corona

$$E_{coro,\pm,r}(r,z,t) = \begin{cases} -E_{f,\pm}(t)\frac{v_\pm^2 t^2 r}{\sqrt{(z-H_{0,\pm})^2+r^2}^3}, & z \lessgtr H_{0,\pm} \mp \sqrt{v_\pm^2 t^2 - r^2} \wedge z \lessgtr H_{0,\pm} \\ -E_{s,\pm}\frac{r}{\sqrt{(z-H_{0,\pm})^2+r^2}}, & z \gtrless H_{0,\pm} \mp \sqrt{v_\pm^2 t^2 - r^2} \wedge z \lessgtr H_{0,\pm} \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

$$E_{coro,\pm,z}(r,z,t) = \begin{cases} -E_{f,\pm}(t)\frac{v_\pm^2 t^2 |z-H_{0,\pm}|}{\sqrt{(z-H_{0,\pm})^2+r^2}^3}, & z \lessgtr H_{0,\pm} \mp \sqrt{v_\pm^2 t^2 - r^2} \wedge z \lessgtr H_{0,\pm} \\ -E_{s,\pm}\frac{|z-H_{0,\pm}|}{\sqrt{(z-H_{0,\pm})^2+r^2}}, & z \gtrless H_{0,\pm} \mp \sqrt{v_\pm^2 t^2 - r^2} \wedge z \lessgtr H_{0,\pm} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

propagating with velocities $v_\pm$ where

$$E_{f,\pm}(t) = E_{max,\pm} + \frac{E_{max,\pm}}{t_{max} - t_0}\left(t - t_{max}\right) \tag{3}$$

is the electric field strength at the corona front, which can be approximated by the fields of those streamers propagated farthest within the streamer coronae (Luque & Ebert, 2014), and $E_{s,\pm} \equiv 0.16E_k$ $(0.31E_k)$ s the stability field at the positive (negative) front (Babaeva et al., 1997; Bazelyan & Raizer, 1998; Cooray, 2015; Kochkin et al., 2016). The mathematical formulation of the corona field is chosen such that the field falls off with $\sim z^{-2}$ ahead of the corona front and is the stability field in the interior of the streamer coronae (Kochkin et al., 2016).

As a sample case, we simulate the acceleration of electrons between streamer coronae where the upper positive streamer corona is initiated at $H_{0,+} = 100$ m propagating downward with $v_+ = 7 \cdot 10^5$ m s^{-1} and where the lower negative corona at $H_{0,-} = 30$ m moves upward with $v_- = 10^5$ m s^{-1}; both coronae are initiated simultaneously after 16.95 μs, which is the approximate time for electrons emitted from the leader tip reaching the upper charge layer at $z = H_{0,+}$. The maximum fields are set to $E_{max,+} = 10E_k$ and $E_{max,-} = 8E_k$, which are upper limits of the maximum electric field at the tips of positive and negative streamers (Kim et al., 2004; Moss et al., 2006; Naidis, 2009; Pancheshnyi et al., 2000) accounting for that the electric fields of positive streamer tips are generally larger than the fields at negative streamer tips (e.g., Luque et al., 2008). For this setup, we perform two simulations: In simulation one, we additionally apply a field of -1 kV cm^{-1} $\approx 0.1E_k$ in the upper charge layer (Marshall et al., 1989) for $z \geq H_{0,+} = 100$ m and decreasing quadratically for smaller z while the second simulation has no additional charge layer field such that electrons are not accelerated further once they enter the upper charge layer. We have chosen two different simulations to give us an idea of how the charge layer influences the photon energies of TGFs.

After 16.67 μs before the two streamer coronae incept, electrons experience the electric field of the leader only. Afterward, the field of the streamer coronae becomes more dominant and enhances the field in-between up to $>12E_k$ before the field collapses after approximately 100 μs, which is in the order of the time difference between the occurrence of TGFs and the main optical pulse, cf. section 2.1.

All simulations have been performed on a high-performance computing cluster using 500 Intel Xeon E5-2680v2 processors.

2.3. Semianalytic Approximation

Since Monte Carlo simulations for the proposed scenario of TGF production take weeks to finish, they are impractical for a parameter study on how the maximum energy and acceleration time of runaway electrons and thus on how the photon energies and the duration of TGFs depend on the inception point of the streamer coronae, their velocities or maximum electric fields.

Therefore, we numerically solve the system of one-dimensional relativistic differential equations

$$\frac{dz}{dt} = v \tag{4}$$

$$\frac{d}{dt}\left(\frac{m_e v}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\right) = e_0\left(E_L(r=0,z) + E_{coro,+,z}(r=0,z,t) + E_{coro,-,z}(r=0,z,t)\right)$$

$$+F_R(v,t) \tag{5}$$

on the symmetry axis $r = 0$ for a test electron with initial position z_0 and initial velocity $v_0 = 10^6$ m s^{-1} until it reaches the upper charge layer at $z = 100$ m. These equations deterministically describe the electron motion sensing the superposed electric field and the friction force F_R in air; thus, the acceleration of electrons, eventually until relativistic energies. Therefore, these equations do not take into account the stochastic nature of electron collisions and energy losses and thus of the runaway process. Still, the solution of Equations 4 and 5 gives a first approximation of the duration and photon energies of TGFs since the superposed electric field of the two encountering streamer coronae, responsible for the acceleration of electrons into the runaway regime, is larger than approximately $8E_k$ for which the friction force as well as the energy loss of electrons become negligible and the production of runaway electrons becomes systematic rather than stochastic. We solve system (4 and 5) with a Matlab script appended as supporting information.

3. Results

Figures 2a and 2b show the position and energy of low-energy electrons traced in the first simulation step bridging the gap between the lightning leader tip and the upper charge layer at $z = 100$ m after approximately 16.9 µs. Until this time step, before the streamer coronae incept, electrons are accelerated in the electric field of a leader with field strengths $\leq 5E_k$ limiting the electron to energies below 200 eV. Electrons with this particular spatial and energy distribution are subsequently initiated for the second simulation step where they are accelerated in the superposed electric field of a lighting leader and two encountering streamer coronae, some of them gaining relativistic energies and emitting energetic γ rays.

Figures 2c–2h show the spatial and energy distribution of electrons and photons between two streamer coronae after approximately 67 µs, panels (c)–(f) in addition with a small charge layer electric field of 1 kV cm^{-1} and panels (g) and (h) without such a charge layer field.

The majority of electrons is confined in the region between the leader tip at $z = 0$ and the upper charge at $z = 100$ m; in this region a fraction of electrons becomes runaway through the electric field of the two encountering streamer coronae. However, the first appearance of runaway electrons is only loosely correlated to the superposed electric field of the lightning leader and the streamer coronae. Because of the stochastic quantum nature of electron collisions with air molecules, there is a small probability of an electron becoming runaway even when the friction force is larger than the electric force, this probability increasing with the electric field strength and therefore with time. Hence, the appearance time of the first runaway electron and thus of the first relativistic beam initiated by this first runaway electron is nondeterministic. Because of the increasing probability of electron runaway, the next acceleration of low-energy electrons to relativistic energies and the resulting runaway beams appear some time after each other which leads to a wave-like pattern with decreasing time difference between the pulses.

Once these energetic electrons reach the upper charge layer, they keep gaining energy in a (potentially) ambient field layer leading to a maximum electron energy of 300 MeV after ≈67 µs (Figure 2d). Since the ratio between the energy of incident electrons and of bremsstrahlung photons is predominantly small (Köhn & Ebert, 2014), these energetic electrons produce photons with energies of maximum 40 MeV. These energetic photons form a beam with a relativistic front and a wave-like pattern (e) as they are produced by those relativistic electrons propagating in wave-like steps; however, because of the continuous photon production through relativistic electrons, the photon beam is smeared out, which will be carried forward while photons propagate through the atmosphere. For this particular case, the photon energy distribution can be fitted through $dN_\gamma/d\varepsilon_\gamma \sim \exp\left(-\varepsilon_\gamma/\varepsilon_{\gamma,c}\mathrm{MeV}\right)/\varepsilon_\gamma$, thus showing a typical TGF pattern (Dwyer et al., 2008), here with a characteristic energy of $\varepsilon_{\gamma,c} \approx 7$ MeV (f).

Panels (g) and (h) show the energy distributions of electrons and photons after 67 µs if there is no additional charge layer field. Since electrons are accelerated between the two streamer coronae only and do not gain

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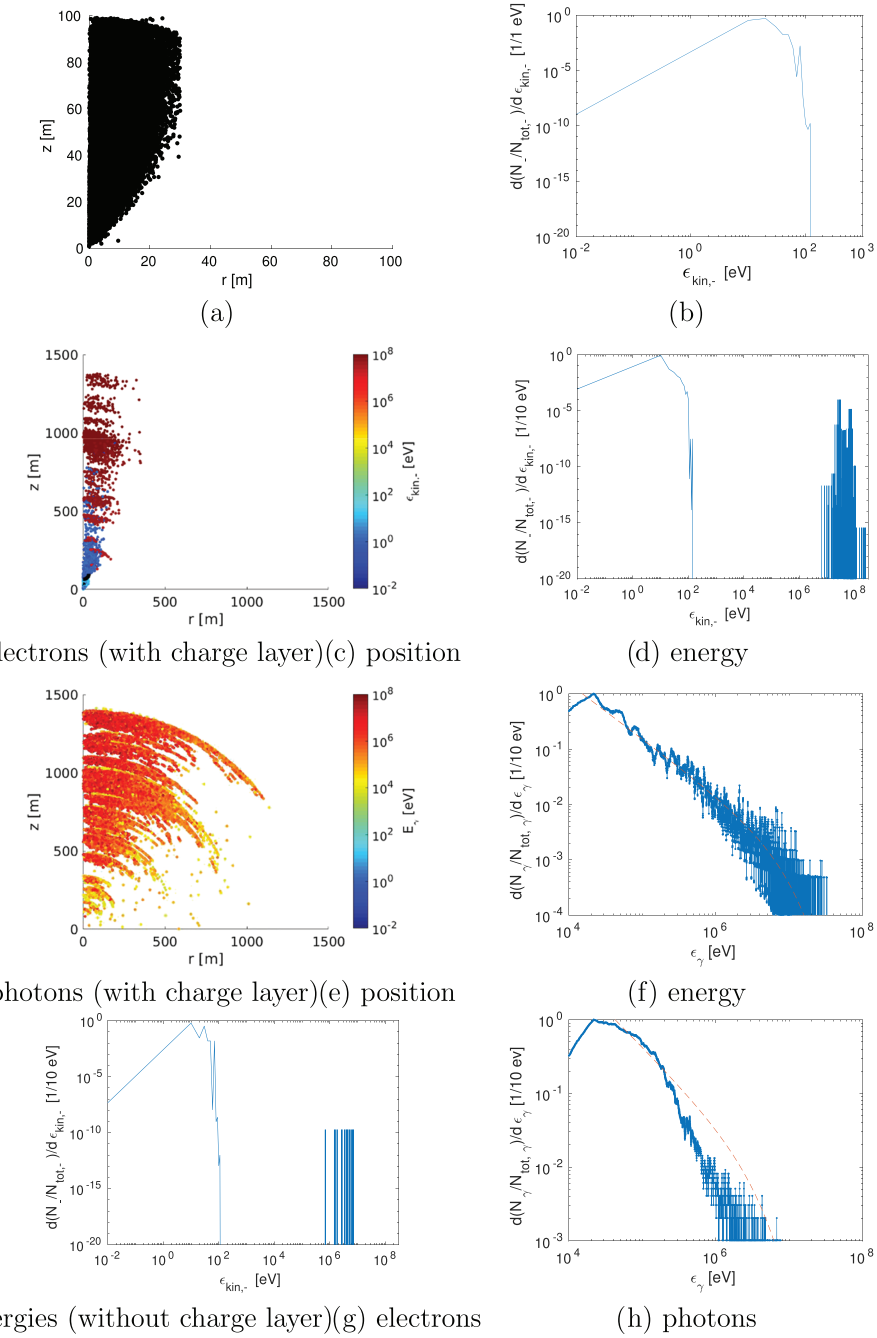

Figure 2. (a, b) The position and energy of electrons in the gap between the leader tip and the upper charge layer after ≈16.9 μs. (c, d) The position and energy of electrons after 67 μs (with an electric field in the charge layer). (e, f) The corresponding position and energy of bremsstrahlung photons after the same time step. (g, h) The energy distributions of electrons and photons after ≈67 μs (without charge layer field). The energy distributions are normalized to the total number $N_{tot,-/\gamma}$ of electrons/photons. In panels (c) and (e) the energy is color coded. The dashed lines in panels (f) and (h) show the fit $\exp(-\varepsilon_\gamma/\varepsilon_{\gamma,c})/\varepsilon_\gamma$.

any additional energy in the upper charge layer, the maximum electron energy is approximately 10 MeV, hence a factor 30 less than with an electric field in the upper layer. Subsequently, the maximum photon energy is 8 MeV with a distribution fit of $dN_\gamma/d\varepsilon_\gamma \sim \exp\left(-\varepsilon_\gamma/3.2\,\mathrm{MeV}\right)/\varepsilon_\gamma$.

Since Monte Carlo simulations take a long runtime and efficiently do not allow for a broad parameter study, we have additionally solved Equations 4 and 5 determining the motion of one single electron between two streamer coronae for various v_-, $H_{0,-}$, z_0 ($t_0 = 50\,\mu$s), $E_{max,+}$, and $E_{max,-}$ as well as for $v_+ = 10^5\,\mathrm{m\,s^{-1}}$ and

$H_{0,+} = 100$ m. For all considered cases, we have determined the maximum electron energy ε_{max}, the time $t_{runaway}$ of when an electron becomes runaway, and the acceleration time t_{accel} as the difference between the runaway time and coronae collision time setting a lower limit of the duration of a resulting TGF.

For all these cases we see that, if runaway electrons as precursors of TGFs appear, they reach electron energies of the order of 10 MeV with acceleration times in the order of tens to hundreds of μs, which is in agreement with the results from the Monte Carlo simulations without any charge layer field yielding maximum electron energies of approximately 10 MeV (cf. Figure 2g). However, ε_{max} decreases in case there is not sufficient space to accelerate electrons to MeV energies or when the peak fields of the streamer coronae are too low. Hence, electrons do not become runaway when the initial position of the negative streamer corona or of the electron is notably close to the upper charge layer where the positive streamer corona incepts such that there is not enough time and space for the electron to accelerate into the runaway regime.

4. Discussion and Conclusion

Based on measurements by the ASIM revealing the relative timing between the occurrence of TGFs, the onset of streamer activity and the main optical pulse of intracloud lightning flashes, we suggest that the production of TGFs is generally related to a large current pulse through the leader step at the onset of optical emission and to the associated streamer activity between the leader tip and the upper cloud charge layer. Hence, we propose the following mechanism for the production of TGFs:

1. Before the leader step, electrons are accelerated up to energies of approximately 100–200 eV by the electric field between the leader tip and the upper charge layer of the cloud.
2. Afterward, streamer coronae of opposite polarity incept in the proximity of the leader tip and the upper cloud charge layer after electrons have bridged the gap between these two.
3. While the streamer coronae develop, their fields increase leading to superposed electric fields significantly high to accelerate electrons into the runaway regime, subsequently emitting energetic bremsstrahlung photons. The field in the upper charge layer accelerates electrons even more determining the maximum photon energies in TGFs.

We have applied a Monte Carlo code to model the aforementioned scenario in two steps: First, we have traced electrons in the field of a lightning leader of 1 km length and with a tip curvature of 1 cm at 10 km altitude until they bridge the gap between the leader tip and the upper charge layer. Subsequently, we have accelerated electrons in the superposed electric field of the lightning leader and the two streamer coronae propagating toward each other, the positive one incepted in the proximity of the charge layer with a maximum front field of $10E_k$ and velocity of $7 \cdot 10^5$ m s^{-1} and the negative one 30 m ahead of the lightning leader tip with a maximum front field of $8E_k$ and a velocity of 10^5 m s^{-1}. We have observed that this configuration alone leads to maximum electron energies of approximately 10 MeV after ≈67 μs with associated TGF photons of comparable energies until they reach the upper cloud charge layer. Depending on the field strength in this charge layer, electrons are capable of reaching higher energies; we have observed that a constant field of 1 kV cm^{-1} in the upper charge layer leads to electron energies of up to 300 MeV with associated photon beams of energies of approximately 40 MeV and an exponentially decreasing photon energy distribution with a characteristic energy of approximately 7 MeV.

Since Monte Carlo simulations take a long time to finish, we have additionally performed a parameter study of the acceleration of a low-energy electron into the runaway regime by solving deterministic equations of motion of a single electron including the motion of two colliding streamer coronae, the associated growth of the electric at the corona fronts as well as the friction force of electrons in air. For the setup mentioned above, we obtain electron energies of approximately 10 MeV until electrons reach the upper charge layer, which agrees well with the performed Monte Carlo simulations. Moreover, we have observed that the exact maximum electron energy depends on the velocity, inception point and electric field of the streamer coronae in addition to the electric field in the positive charge layer. When the streamer coronae approach each other too fast or when the electron is initially positioned too close to the positive streamer corona, there is not enough space and time to accelerate electrons to relativistic energies.

This effect is similar to the acceleration of electrons between two encountering streamers suspect to the production of X-rays in laboratory discharge experiments. While estimates for the streamer activity within a 1 m gap suggest that electrons might be accelerated to energies of approximately 1 MeV if the maximum voltage is ≈1 MV (Cooray et al., 2009; Kochkin et al., 2012), microscopic simulations of encountering streamers indicate that the collision of two streamer fronts and the subsequent growth of the superposed electric field happens so fast that there is not sufficient time to accelerate electrons to energies beyond 1 keV (Ihaddadene & Celestin, 2015; Köhn et al., 2017a) (Babich & Bochkov, 2017).

The time difference between the occurrence of a TGF and its associated main optical lightning pulse as well as the duration of TGFs is correlated with the collision time of the streamer coronae. Yet, the time difference can be larger than this collision time since the lightning leader needs additional time to step after the merge of the two opposite streamer coronae. Similarly, the duration of TGFs is longer than the acceleration time of electrons, limited by the coronae collision time, since energetic electrons continue propagating in the upper charge layer even after the encounter of the streamer fronts and therefore keep generating bremsstrahlung photons. In all considered cases where relativistic electrons occur, we have observed acceleration times of tens to hundreds of μs serving as the minimum duration time of TGFs.

Conclusively, the mutual observation of TGFs by ASIM and computational simulations of electron acceleration suggest a solution to the enigma which mechanism might produce TGFs: the acceleration of electrons in the two oppositely charged, encountering streamer coronae associated to the leader step with a large current pulse such that lightning illuminates. Together, observations and simulations have shown that this physical scenario explains the production of electrons and photons with energies of tens of MeV, typical photon energy distributions of TGFs as well as TGF durations and time differences between the occurrence of TGFs and the lightning's main optical pulse in the order of tens to hundreds of μs, all in agreement with previous and current observations (Alnussirat et al., 2019; Briggs et al., 2010; Cummer et al., 2011, 2015; Gjesteland et al., 2017; Østgaard et al., 2019).

Data Availability Statement

The data used for this publication can be obtained online (from https://doi.org/10.5281/zenodo.3922179).

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