Terrestrial gamma ray flash production by active lightning leader channels

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[1] The production of terrestrial gamma ray flashes (TGFs) requires a seed energetic electron source and a strong electric field. Lightning leaders naturally provide seed electrons by cold runaway and strong electric fields by charge accumulation on the channel. We model possible TGF production in such fields by simulating the charges and currents on the channel. The resulting electric fields then drive simulations of runaway relativistic electron avalanche and photon emission. Photon spectra and directional distributions produced by the model agree qualitatively with observations. Simulations with a variety of initial conditions indicate sufficient electric fields are produced if an unbranched channel supports a current pulse of at least 100 kA such as occurs if the channel is at least 1 km long and embedded in an ambient electric field of at least 100 kV m^{-1}. The mechanism does not strongly depend on altitude as friction and characteristic electric field strengths scale similarly. Seed particle production is not directly simulated, but estimates of seed production rates suggest current pulse activity of ~1 ms duration can account for TGF-scale emission.

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1. Introduction

[2] Terrestrial gamma ray flashes (TGFs) [*Fishman et al.*, 1994] are ~1 ms pulses of gamma rays observed by satellites. Typically, these pulses are detected less than 3 ms from measurable electrical activity, while geolocations of this correlated electrical activity are usually less than 300 km from the subsatellite point [*Inan et al.*, 1996; *Cummer et al.*, 2005; *Inan et al.*, 2006; *Cohen et al.*, 2006, 2010]. Such closely correlated electrical activity indicates a close association with lightning, possibly intracloud lightning [*Stanley et al.*, 2006]. The TGF photon spectrum ranges from below 20 keV to at least 40 MeV [*Smith et al.*, 2005; *Marisaldi et al.*, 2010; *Briggs et al.*, 2010] and indicates a source altitude of 15–

feedback [*Dwyer*, 2003, 2008]. If such feedback occurs, the number of avalanches can grow extremely rapidly and produce copious bremsstrahlung until the increased conductivity produced by the avalanches cause the electric field to decay, a process that takes less than 0.1 ms depending on the electric field strength [*Dwyer*, 2007]. This relativistic feedback can only develop if the potential difference in the strong field region itself covers at least 50–100 MV [*Carlson*, 2009, p. 91]. This condition may be difficult to meet in thunderstorms, as it requires focusing almost the entire thunderstorm potential, typically $\lesssim$100 MV [*Marshall and Stolzenburg*, 2001], over a 100 m region.

[5] Lightning itself is another possible way to meet the requirements for TGF production, as it both involves strong electric fields and produces seed relativistic electrons. Dielectric breakdown processes such as lightning involve avalanche growth of populations of low-energy electron, a phenomenon that only occurs in electric fields stronger than ~3 MV m^{-1} in air at sea level [*Raizer*, 1997, p. 135]. Such avalanches act to locally intensify the electric field near the tip of the avalanche and can produce propagating ionization waves called "streamers" [*Bazelian and Raizer*, 1998, p. 43]. The possibility that such locally intensified electric fields might exceed the cold runaway threshold is seen in both theoretical calculations where runaway electrons are recorded [*Moss et al.*, 2006; *Li et al.*, 2009; *Chanrion and Neubert*, 2010] and laboratory experiments where energetic X-rays from runaway electron bremsstrahlung are detected [*Nguyen et al.*, 2008; *Dwyer et al.*, 2008]. X-rays indicative of cold runaway are also detected in coincidence with leader development in natural and triggered lightning [*Moore et al.*, 2001; *Dwyer et al.*, 2003; *Dwyer*, 2004; *Dwyer et al.*, 2005]. Overall these facts indicate that lightning leader channels may not only produce strong electric fields, but may also drive cold runaway as a source of seed electrons for RREA and thus meet the requirements for TGF production.

[6] In this paper we model TGF production by lightning leader channels. TGF production in the context of lightning leaders has previously been discussed and argued as feasible [*Williams et al.*, 2006], with some basic calculations given by *Moss et al.* [2006], *Gurevich et al.* [2007], *Dwyer* [2008], and *Dwyer et al.* [2010]. These initial studies give high-level arguments for the possibility of TGF production seeded by lightning leaders, especially when large ambient electric fields are assumed to be present. Here instead of assuming large ambient fields, we focus on the electric fields due to the lightning channel itself, an idea outlined by *Moss et al.* [2006] and discussed further by *Carlson et al.* [2009]. In this work we present a two-phase model of TGF emission by lightning leaders. First, we model the time evolution of the electric fields near leader channels. We then inject seed electrons into these electric fields and run Monte Carlo simulations of the resulting RREA and bremsstrahlung. The results indicate that TGF-like emissions can indeed be produced subject to reasonable minimum intensity constraints.

2. Electric Field and RREA Model

[7] The electric field of the leader channel is dominantly produced by the charge density of the channel. This charge is driven to flow by electric fields exerted by cloud charges and charges elsewhere on the channel. Induction effects also occur, limiting current changes and producing current pulse reflections at channel discontinuities. This complicated charge dynamics can be entirely expressed by the electric field integral equation (EFIE):

$$\mathbf{E}_{\mathrm{t}}(\mathbf{x},t) = \frac{1}{4\pi\epsilon_0}\int d^3x' \left\{ \frac{\hat{\mathbf{R}}}{R^2}[\rho(\mathbf{x}',t')]_{\mathrm{ret}} + \frac{\hat{\mathbf{R}}}{cR}\left[\frac{\partial\rho(\mathbf{x}',t')}{\partial t'}\right]_{\mathrm{ret}} - \frac{1}{c^2R}\left[\frac{\partial\mathbf{J}(\mathbf{x}',t')}{\partial t'}\right]_{\mathrm{ret}} \right\} \quad (1)$$

where $\mathbf{E}_{\mathrm{t}}$ is the total electric field, ρ is the volume charge density, $\mathbf{J}$ is the current density, $\mathbf{x}$ and $\mathbf{x}'$ are position vectors, $\mathbf{R} = \mathbf{x} - \mathbf{x}'$, $R = |\mathbf{R}|$, $t' = t - R/c$, $\hat{}$ signifies unit vectors, and $[\cdots]_{\mathrm{ret}}$ represents evaluation in retarded time (t'). The EFIE relates the electric field to the charges and currents. Ohm's law and charge conservation close the system. We solve the system on arbitrary lightning channels with the method of moments. First, the channel is divided into short segments and the current and charge densities are assumed constant on the segments. The geometric integral in the EFIE is then evaluated using the thin wire approximation [*Miller et al.*, 1973] to give the electric field at the midpoint of each segment. This leaves a set of algebraic equations, each relating the present electric field at a given segment to the past and present charge and current values on the segments. Ohm's law and charge conservation are then used to express the electric fields and charges in terms of currents. The net result is a system of algebraic equations relating past and present currents on segments to each other. This system can be solved to determine the present currents, and the process can be repeated to step the system forward in time. More detail can be found in chapter 6 of *Carlson* [2009].

[8] This model predicts the time evolution of the charges and currents on the channel. These charges and currents can be used to calculate electric fields, but the use of the thin wire approximation in the EFIE limits the validity of these fields very near the channel. The accuracy of near-channel fields is also limited by the outward flow of charge carried by corona and streamer discharge. These discharges act to limit the electric field near the leader to a characteristic maximum field of order the conventional breakdown threshold (3 MV m^{-1} at sea level) over a timescale of 5–10 μs. At earlier times, higher electric field limits are appropriate. In this paper, we use 10 MV m^{-1} sea level equivalent, corresponding to a timescale of order 2 μs. These limits apply over a region several meters in radius surrounding the leader channel, the same region where the thin wire approximation breaks down. We therefore calculate the electric fields near the leader channel using the thin wire approximation as before but limit the maximum electric field to ~10 MV m^{-1} sea level equivalent.

[9] In order to consider the effects of known current pulses on various channels at various altitudes, it is useful to separate the electric field produced by the channel from the ambient electric field. This separation is treated here by applying an external field to the channel but not to its surroundings and simply implies a lightning channel that carries current away from the source into a different environment. The result is a space- and time-dependent electric field given an initial channel length and altitude, an ambient electric field strength, and a desired current pulse magnitude.

[10] These fields are evaluated over a space and time range of interest near the tip of the channel. RREA seed particles with energies of order 100 keV such as may be produced by cold runaway in the inner strong field region are then injected into the time-varying field. The resulting RREA is simulated with GEANT4, a particle physics Monte Carlo simulation tool including all relevant physics for electrons, photons, and positrons with energies above 250 eV [*Agostinelli et al.*, 2003]. The RREA simulation predicts the avalanche growth, feedback, X-ray emissions, and their time dependence.

[11] The model thus predicts the energetic electron and X-ray emissions produced by the electric fields near leader channels. Though the model does not directly include the physics of seed production or the complicated streamer and corona discharge phases involved in leader extension, the model does approximate the overall dynamics of the strong field regions surrounding leader channels. The X-ray emissions predicted by the model during intense current and charge activity on the channel can then be compared with TGF emissions. Any match or mismatch between TGF observations and the model predictions can therefore be used to constrain the parameters of the model and thus assess the role of lightning leaders in TGF production.

3. TGF Production Simulations

[12] In order to assess the production of TGFs by lightning leaders, the simulations described above require a range of meaningful initial conditions: effective channel radius for the thin wire approximation, ambient electric field, channel geometry, channel location, and any initial charges and currents present on the channel. In order to focus on the mechanism, these initial conditions are kept as simple as possible. The effective channel radius is taken to be 0.5 m, though variation of this parameter does not significantly alter the results. The initial ambient electric field is taken to be uniform, directed downward, and with magnitude less than the runaway relativistic electron avalanche threshold. Though complex channel geometry can be simulated within our framework, here we use straight, unbranched, vertical channels. The length of the channel is varied from 100 m to 3 km. The channel is placed with its upper tip at altitudes ranging from 0–20 km above sea level. The channels are left initially uncharged and with no initial current. Such initial conditions are admittedly unphysical as lightning leader channels do not extend instantaneously. However, such initial conditions produce reasonable current pulses, and the current pulse is the main driver of charge density and electric field intensification near the channel tip.

[13] The electric fields produced near the channel under these initial conditions are then simulated. These fields are most intense during the peak of the charge density reached several microseconds after the simulation is started and the first current pulse stops.

[14] Seed electrons of various momenta are then injected at various positions in the electric field. Though the seed particle population and its properties in principle depend on the activity of the leader channel, we simply inject representative runaway electrons near the leader channel at various times and report the resulting RREA and bremsstrahlung emissions. These postulated seed particles are injected with energy ~200 keV. The resulting avalanches produced by these seeds can then be scaled up to match seeds derived from detailed analysis of seed production.

[15] Sample results for a 1 km long leader channel at 10 km altitude with a 50 kA current pulse in a 37 kV m^{-1} electric field are shown in Figure 1. The current, charge density, and electric field near the tip of the channel are shown in Figures 1a–1c. The positions and directions of photon production in sample avalanches initiated at 1–3 μs by seed particles injected on one side of the channel are shown in gray and black, respectively, in Figure 1d. The corresponding photon spectra are shown in Figure 1e. The duration of the high-intensity emissions correlates well with the duration of the intense current pulses. The directional distribution of photons is broad, as shown in Figure 1f.

4. TGF Observation Comparison and Source Constraints

[16] The broad hard energy spectrum produced at peak intensity for the sample simulations as shown in Figure 1e is in good qualitative agreement with the TGF source spectrum shown by *Carlson et al.* [2007] to be consistent with TGF observations. The maximum photon energy produced (~16 MeV) is lower than the highest energies in the TGF source spectrum from *Carlson et al.* [2007] (~20 MeV), suggesting more intense initial conditions may be required, but overall agreement is good. Broad directional distributions as shown in Figure 1f produced by the diverging electric fields near lightning channels are also favored in comparison to TGF observations [*Dwyer and Smith*, 2005; *Carlson et al.*, 2007; *Hazelton et al.*, 2009]. The duration of emissions predicted by our model is shorter than the typical TGF source duration, but longer durations may be explained by longer current pulse durations produced by periods of dynamic leader activity not captured in our simulations of static, nonextending channels.

[17] Though our model results shown above qualitatively match TGF data quite well, this is not the case for all initial conditions. This match or mismatch allows us to constrain the initial conditions. First, the produced photon spectrum must be consistent with satellite observations. In particular, the maximum electron energy in the RREA must meet or exceed the energy of the observed highest-energy photons (40 MeV). Therefore, 40 MeV is a lower limit on the possible electron energy gain over the high field region. Similarly, RREA growth of seed particle populations must result in at least 10^{17} energetic electrons to match observed TGF intensity. Estimates of leader seed production are a necessary input to this analysis and can be derived either from theory or experiment. Theoretical estimates range from 10^{18} s^{-1} by *Moss et al.* [2006] to 10^{19} s^{-1} by *Gurevich et al.* [2007]. Comparison of X-ray observations of triggered lightning dart leaders to simulated bremsstrahlung from monoenergetic 1 MeV electrons gives an estimated seed production rate of ~10^{16} s^{-1} [*Saleh et al.*, 2009]. The discrepancy between theory and experiment is likely a result of comparing experimental results that detect higher-energy electrons most efficiently to theoretical results that focus on lower-energy thermal runaway electrons. The effective seed production rate for natural lightning leaders at cloud altitude is probably somewhere in between the experimental and theoretical numbers; here we must content ourselves by giving ranges.

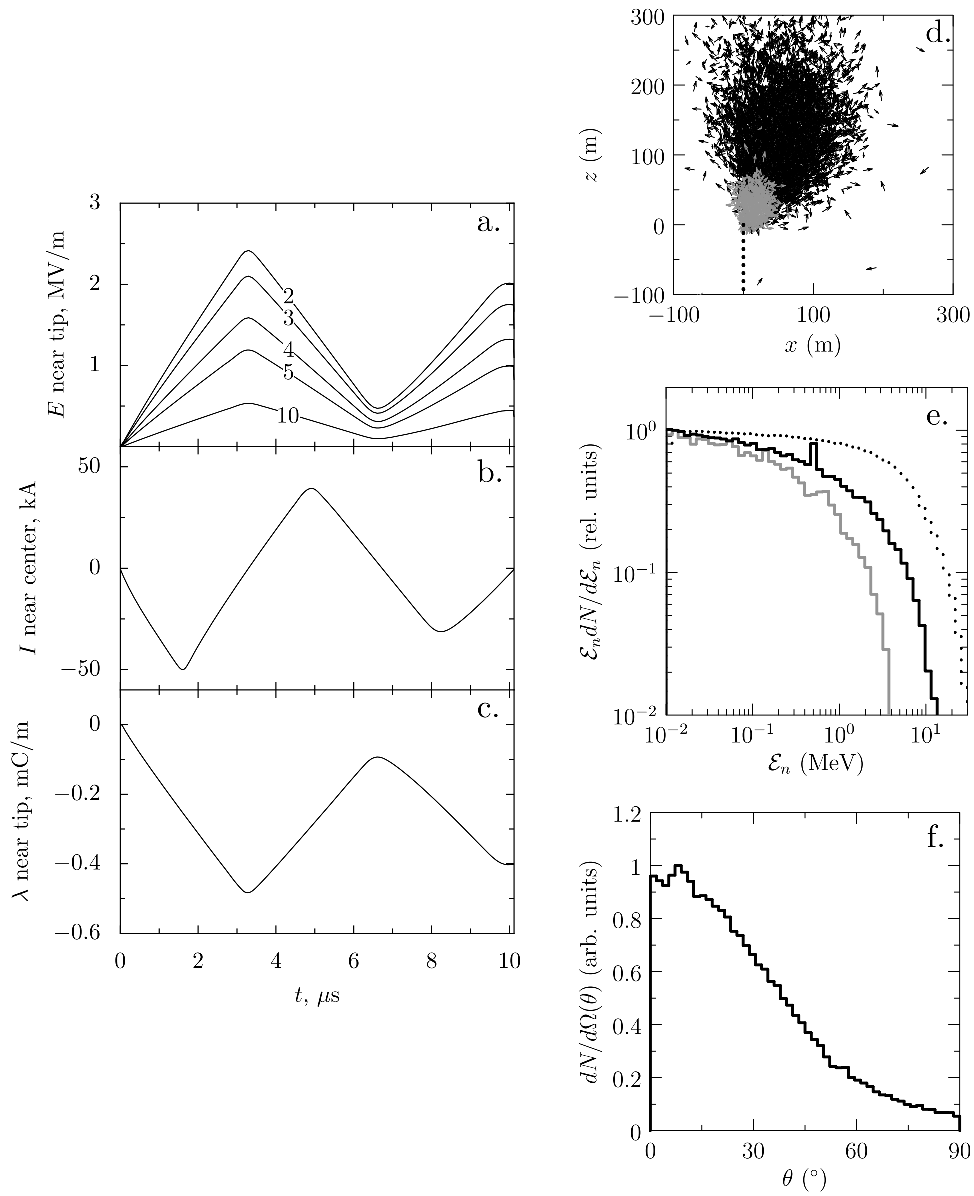

Figure 1. Sample results for a 1 km channel at 10 km altitude, 50 kA current pulse, and 37 kV m^{-1} electric field ($\delta \sim 0.5$). (a) Electric field at 2, 3, 4, 5, and 10 m from the channel tip as marked. (b) Current near the center of the channel. (c) Linear charge density on the channel near the channel tip. (right) Sample RREA simulation results. (d) Photon production locations and directions for electron injections at 1 (gray) and 3 μs (black) with the channel location shown as a dotted line. (e) Corresponding energy spectra of photons produced, with a RREA bremsstrahlung spectrum consistent with TGF observations shown as a dotted line, all normalized to 1 at low energy. (f) Photon initial directional distribution.

Over the ~1 ms timescale of a TGF, we therefore consider 10^{13}–10^{16} seed particles, requiring avalanche multiplication factors $\mathcal{M} \gtrsim 10^1$–10^4 to match TGF observations.

[18] These requirements on electron energy gain over the high field region and the avalanche growth factor can be treated approximately by integration of these properties along possible electron trajectories. The energy gain can be approximated simply as $\int (qE - F)dl$, where qE is the electric field force, F is the frictional force, and dl is a length element along an electron trajectory. The RREA growth factor [$\mathcal{M}$] can be approximated as $\exp(\int dl/\lambda)$, where λ is the avalanche length scale given by *Coleman and Dwyer* [2006]. Here electron trajectories are approximated as moving at the speed of light along electric field lines.

[19] Repeating these calculations for different initial conditions and finding the maximum over initial seed electron positions gives the maximum electron energy gain and avalanche multiplication factors as a function of peak current, altitude, ambient electric field, and channel length. Contour plots of energy gain and avalanche multiplication factor are shown for zero applied electric field and 1 km channel length in Figures 2 and 3. Simulations with nonzero applied electric fields (data not shown) naturally produce larger energy gain and avalanche growth, but the dependence is weak since most

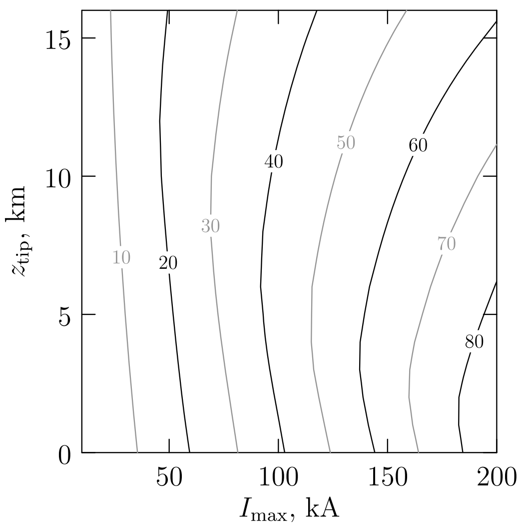

Figure 2. Contour plot of the altitude and current pulse dependence of the maximum possible energy gain for electrons injected near the tip of a 1 km lightning leader channel. Contour labels indicate energy gain in MeV.

energy gain and avalanche multiplication occurs in the high field region close to the channel.

[20] These plots naturally show more intense high-energy phenomena at higher applied electric field and higher peak current but also show a small preference for lower altitude channels. Low-altitude channels are slightly favored because of the altitude dependence of the maximum electric field cutoff used in our simulations; for a given current pulse strength, lower altitudes have higher maximum fields implying higher overall potentials. Lower altitudes also involve higher frictional losses, partially offsetting the higher available potential, leaving only a weak altitude dependence.

[21] Overall, maximum photon energies exceed 40 MeV for current pulse amplitudes above 100 kA, with lower maximum energies requiring smaller current pulses. Avalanche growth factors exceed 10^1 when the associated current pulse is stronger than 50 kA and exceed 10^4 for current pulses larger than 150–175 kA. Current pulses larger than 100 kA are not produced by our EFIE solution except in channels longer than 1 km in electric fields stronger than 100 kV m^{-1}. These can be treated as rough minimum intensity constraints on the source lightning activity necessary to produce a TGF. Smaller current pulses associated with shorter channels and smaller electric fields do not sufficiently intensify the electric field to generate large populations of high-energy photons.

[22] The altitude dependence of maximum X-ray energy and avalanche growth favors low altitudes but only weakly. These results suggest that significant RREA growth and gamma ray production are possible in the electric fields near isolated leader channels regardless of altitude. If sufficient seed particles are present in these fields, large gamma ray pulses will be produced.

5. Discussion

[23] The model described above predicts significant energetic photon emission consistent with TGF observations if the source lightning involves $\gtrsim$100 kA peak currents as occur on channels $\gtrsim$1 km long in ambient electric fields $\gtrsim$100 kV m^{-1}. Larger current pulses may be required if the seed population necessitates avalanche growth factors $\gtrsim$100, but larger current pulses are also likely accompanied by photon spectra with maximum energy above the maximum observed photon energy of ~40 MeV. Lower maximum photon energies correspondingly can be produced with smaller current pulse amplitudes. These requirements for source lightning are much more reasonable than the requirements made by the QES and EMP mechanisms mentioned above. The conditions required for production of 100 kA current pulses may also be less stringent than the ~100 MV confined electric fields required by TGF production by RREA relativistic feedback, though note that our simple model of current pulses also requires 100 MV to produce a 100 kA current pulse (1 km channel in an applied 100 kV m^{-1} electric field). Given the close observed time coincidence between lightning and TGFs and the relatively reasonable constraints placed by our model, this suggests that TGFs are indeed emitted in the strong electric fields directly produced by active leader channels.

[24] Strong current pulses may be driven on leader channels by the strong electric fields that led to initiation or by rapid extension of leaders into densely charged regions. This picture suggests TGF production early in the development of the discharge. TGF production later in the discharge may also be possible if current pulse activity is sufficiently focused on individual channels, but this may not occur in extensively branched leader channel networks. Large current pulses are common as return strokes, for instance, but such current pulses may not focus their activity on single channel tips sufficiently to drive TGF production as simulated here.

[25] Our model thus predicts emissions originating in the strong fields near leader channels in coincidence with leader activity driven by intense current pulses. Recent studies of electrical activity associated with TGFs unfortunately does

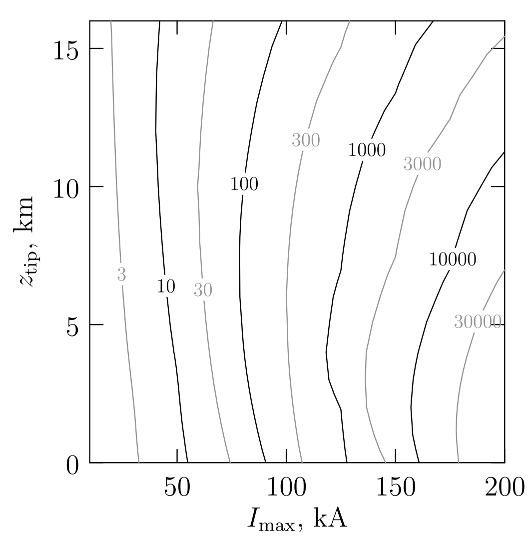

Figure 3. Contour plot of the altitude and current pulse dependence of the maximum avalanche growth of populations of runaway electrons injected near the tip of a 1 km lightning leader channel. Contour labels indicate the avalanche growth factor $\mathcal{M}$.

not provide a single clear hypothesis. Very low frequency (VLF) radio observations by *Cohen et al.* [2010] show a very close association between radio atmospherics and TGFs with a ~1 ms time variance in almost all cases, and many cases are consistent with powerful cloud-to-ground lightning. *Lu et al.* [2010] present very high frequency lightning mapping array data combined with ultralow-frequency (ULF), VLF, and low-frequency (LF) radio observations for a TGF-associated intracloud lightning discharge and conclude that TGF production was associated with the initial upward development of an energetic leader and was closely associated with a burst of electrical activity including a discharge measured by the national lightning detection network as 36 kA. *Shao et al.* [2010] give results of VLF/LF observations of lightning coincident with TGFs and conclude that TGFs are typically associated with current pulse magnitudes below 20 kA though high-current narrow bipolar events are sometimes also coincident. These results are both consistent and inconsistent with our model in that leader development and large current pulses are implicated but that the current pulse magnitudes are sometimes too small according to some observations. From the perspective of our mechanism, smaller current pulses are still capable of generating observable gamma rays, but the population of energetic electrons will not grow as large and the photon spectrum will have a lower maximum energy unless additional acceleration in ambient fields is possible. Further observations, especially with more accurate timing of satellite observations will be required to make definitive statements about the activity (or lack thereof) coincident with TGFs.

[26] The model presented above is limited in two main ways. First, seed particles produced by the leader channel are assumed and are simply injected near the channel. This assumption ignores any dependence of the seed production process on the state of the channel and may not adequately treat the transition and acceleration of seed particles from small high field regions to the larger fields treated here. Second, the physics of channel extension is not included in the model. In lab sparks, this extension involves intense processes such as corona flashes and space leader formation and propagation [*Gallimberti et al.*, 2002], processes that may increase the effective seed population by accelerating lower-energy electrons up to seed energies [*Moss et al.*, 2006]. The intense electric fields in such processes should be comparable in magnitude and dynamics to the fields simulated here but may be more intense, cover a large volume, or involve physics more likely to produce seed runaway electrons. A future model to address this domain would require treatment of the tip of the lightning channel, production and propagation of multiple streamers, space leader production and growth, seed production, and RREA in the overall fields.

[27] In summary, we present a model of TGF production driven directly by active lightning leaders. The model allows us to determine the source lightning properties necessary to produce TGFs. The model predicts gamma ray emissions consistent with all TGF observations only if the source lightning currents are $\gtrsim$100 kA. These constraints are as reasonable as recent mechanisms and are broadly consistent with observations of lightning associated with TGFs. The X-ray emissions predicted by the model are broadly consistent with satellite observations of TGFs. Further analysis should include more detailed treatment of the physics of cold runaway seed production and the development and extension of the lightning channel.

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