Modelling the production of terrestrial gamma-ray flashes during the final leader step

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Outline

• TGFs, ASIM and ground based measurements
• Length scales in thundercloud
• Monte Carlo simulations
  – Electron motion in lightning leader field
  – Electron acceleration between two colliding streamer coronas
• Simulation results
  – Spatial and energy distribution of electrons and photons
• Parameter study
• Conclusions
Introduction: ASIM and TGFs
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Photometer plots: i) 337 nm associated to streamer activity; ii) 777 nm associated to leader activity (more details on measurements: see presentation EGU2020-2467)

TGF occurs close to onset of streamer activity

Time difference between TGF occurrence and main optical pulse in the order of 100 µs
Ground-based measurements

\[ t_{\text{discharge}} - t_{\text{TGF}} \leq 500 \, \mu s \]

\[ \Delta t_{\gamma,\text{onset}} \leq 100 \, \mu s \]

\[ \Delta t_{\gamma,\text{fit}} \leq 60 \, \mu s \]

Characteristic length scales

Positive streamer corona moving downwards

Final leader step

Negative streamer corona moving upwards

$\Delta t \approx 100 \, \mu s$ => $v_{\text{leader}} \approx 10^6 \, \text{m s}^{-1}$ => $L \approx 100 \, \text{m}$
Two step simulation

i) inject electrons at $5E_k \Rightarrow$ get spatial and energy distribution of low-energy electrons with MC particle code

trace electrons until they reach the upper charge layer (here at $z=100\text{m}$)
Two step simulation

ii) turn on negative and positive streamer coronae

\[ E_{\text{coro}} \sim \begin{cases} E_0(t) \frac{1}{r^2}, & \text{if outside} \\ E_{\text{stability}}, & \text{if inside} \end{cases} \]

\[ E_{\text{coro}} \approx 0.1 E_k \]

\( L \approx 100 \text{ m} \)

Evolution of on-axis electric field

Fronts moving $\Rightarrow$ region of $E_{\text{stability}}$ increases

Corona encounter $\Rightarrow$ locally highly enhanced electric field (above $10E_k$)

A. Luque et al., 2017. JGR Atmos., vol. 122, pp. 10497–10509]
Spatial and energy distribution of low-energy electrons after 16.7 µs
(before streamer inception)

Electrons bridge the gap between the leader tip (z=0) and the upper charge layer (z=100)

- maximum of energy distribution at ≈ 20 eV
- maximum energy ≈ 100 eV

=> use these electrons as input for second MC simulation (with streamer coronae)
Spatial and energy distribution of electrons after 65 µs (after streamer inception)

- first appearance(s) of runaway electron (and thus of relativistic beam) random (but probability increases with time/increasing electric field of coronae fronts) => wave-like pattern
- because of growing field, wave smears out (more frequent production of runaway electrons)
- majority of electrons with energies < 100 eV
- some very energetic electrons ($E_{\text{max}} \approx 300$ MeV)
- gap because randomly produced runaway electrons keep getting accelerated
Spatial and energy distribution of photons after 65 µs
(after streamer inception)

- photon beam follows energetic electrons
- continuous production through Bremsstrahlung => less wave-like pattern than for electrons (beam smeared out)
- maximum photon energy ≈ 40 MeV
- photon distribution can be fitted through \( \frac{dN_\gamma}{dE_\gamma} \sim \exp(-E_\gamma/E_{\gamma,0})/E_\gamma \) with \( E_{\gamma,0} \approx 5.5 \) MeV
Energy distribution of electrons and photons without charge layer field

- Similar energy distribution as with charge layer field, but maximum energy $\approx 20$ MeV (instead of 300 MeV)

- Maximum photon energy $\approx 20$ MeV
- Photon distribution can be fitted through $dN_{\gamma}/dE_{\gamma} \sim \exp(-E_{\gamma}/E_{\gamma,0})/E_{\gamma}$ with $E_{\gamma,0} \approx 3.2$ MeV
Parameter study I

- Monte Carlo simulations are time consuming, thus not practical for parameter study

- To get an estimate on maximum electron energy and beam duration, solve set of 1D deterministic differential equations describing electron motion in a given electric field (including friction force) with initial conditions \( z(t_0=50 \mu s)=z_0 \) and \( v(t_0=50 \mu s)=10^6 \) m s\(^{-1}\):

\[
\frac{dz}{dt} = v
\]

\[
\frac{d}{dt} \left( \frac{m_e v}{\sqrt{1 - \left( \frac{v}{c} \right)^2}} \right) = e_0 \left( E_L(z) + E_{\text{coro},+}(z,t) + E_{\text{coro},-}(z,t) \right) + F_R(v,t)
\]

- Field of lightning leader
- Electric field of positive and negative streamer corona
- Friction force
Parameter study II

maximum electron energy (left y-axis), time \( t_{\text{runaway}} \) when electron becomes runaway and acceleration duration \( t_{\text{accel}} \) (right y-axis)

Initial conditions:
max. front fields: \( E_{\text{max},-} = 8E_k, E_{\text{max},+} = 10E_k \)

Inception positions: \( H_{0,+} = 100 \text{ m}, H_{0,-} = 30 \text{ m} \)

front veloc.: \( v_+ = 7 \cdot 10^5 \text{ m s}^{-1}, v_- = 10^5 \text{ m s}^{-1} \)

- energies of approx. 10 MeV
- accel. duration of approx 50 µs
- no runaway electrons when \( z_0 \) too close to \( H_{0,+} \)

- energies of approx. 5 MeV
- accel. duration of approx 50-500 µs
- no runaway electrons when \( v_- > 5 \cdot 10^5 \text{ m s}^{-1} \)
Conclusion

- Simulations confirm relation between production of TGFs and leader-streamer activity (as seen by ASIM)
- TGF duration at least tens of $\mu$s
- Maximum photon energy tens of MeV (and typical photon energy distribution)
  
  => good agreement with current and previous measurements
- Cloud charge layer field determines maximum electron/photon energy
- Parameter study: Need enough space between streamer coronae for electrons to become runaway (otherwise no TGFs)