Recent developments on TGF production models

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Introduction

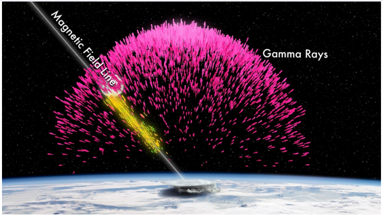
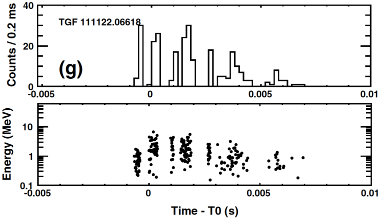


Illustration of a TGF. Credit: NASA/Goddard Space Flight Center



Example of a multi-peak TGF detected by AGILE [*Marisaldi et al.*, JGR, 119, 1337, 2014]

- Typical max. energy: ∼30 MeV.
  - Max. energy reported (AGILE): 100 MeV ! [*Tavani et al.*, PRL, 106, 018501, 2011].
- Typical duration: fraction of ms.
  - t_{50}-duration distribution peak reported between ∼100 μs (Fermi) [*Fishman et al.*, JGR, 116, A07304, 2011] and ∼200 μs (AGILE) [*Marisaldi et al.*, 2014].
- Typical fluence: $\gtrsim$1 photon/cm^2 when observed from low-orbit.
  - The maximum TGF fluence is yet to be established (due to deadtime, pile-up, etc.).

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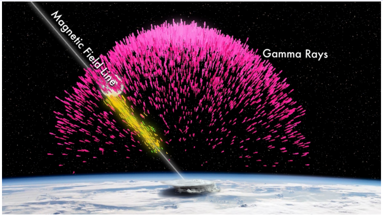
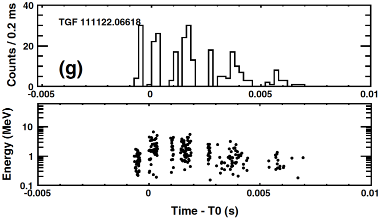


Illustration of a TGF. Credit: NASA/Goddard Space Flight Center



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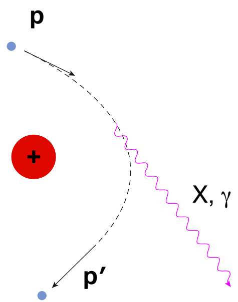
What is the origin of these energetic radiation bursts?

Introduction

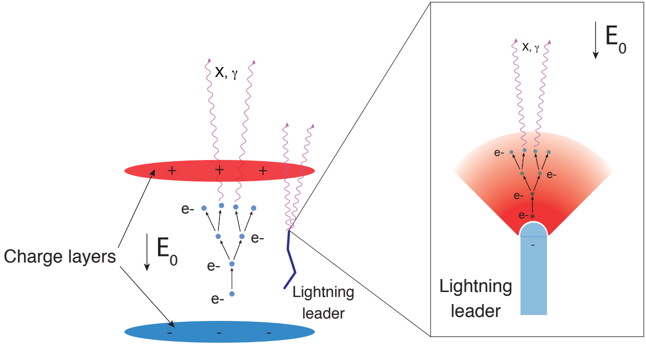
- TGF spectrum is consistent with bremsstrahlung emission (or “braking radiation”) from energetic electrons.



Bremsstrahlung emission process.

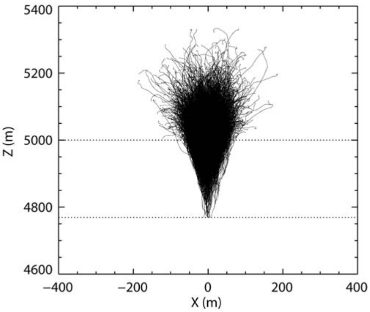
- Production of energetic electrons in the atmosphere?

Two theories to explain TGFs



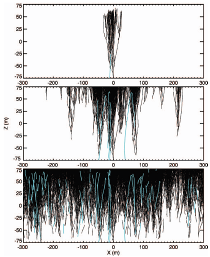
RREA in thunderstorm weak electric field [e.g., *Dwyer*, JGR, 113, D10103, 2008]

Thermal runaway electrons in the leader field [e.g., *Celestin and Pasko*, JGR, 116, A03315, 2011]



[*Dwyer et al.,* JGR, D09206, 2010, Figure 1].

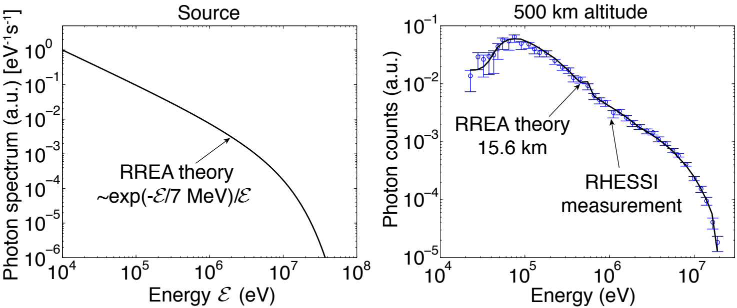
- RREA seeded by energetic electrons produced by cosmic rays [*Gurevich et al.*, Phys. Lett. A., 165, 463, 1992] has been believed to produce TGFs since their discovery in 1994.
- *Dwyer et al.* [JGR, 113, D10103, 2008] demonstrated that TGFs cannot be produced by relativistic runaway electron avalanches acting on natural background radiation or extensive cosmic-ray air showers alone.



[*Dwyer*, Phys. Plasmas, 14, 042901, 2007, Figure 2].

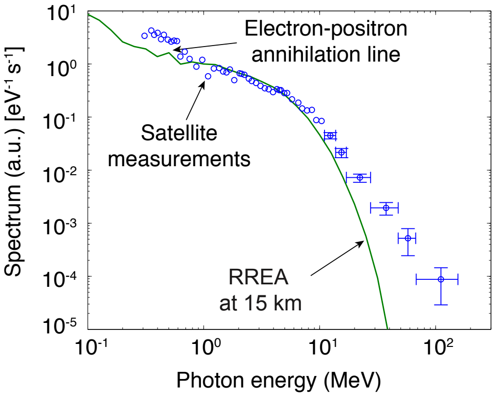
- Relativistic feedback: gamma-rays can create new runaway electrons by Compton scattering, electron-positron pair production, 2nd order feedback from positron's bremsstrahlung or annihilation.
- Self-propagating *relativistic feedback streamer* has been suggested to occur for large potential differences [*Dwyer*, JGR, 117, A02308, 2012; *Liu and Dwyer*, JGR, 118, 2359, 2013].
- Feedback requires electric fields $>$4 kV/cm ($\times N/N_0$) extending over several kilometers [e.g., *Skeltved et al.*, JGR, 119, 9174, 2014], while measurements show ambient electric fields $<$2 kV/cm ($\times N/N_0$) in thunderclouds [e.g., *Marshall et al.,* JGR, 100, 7097, 1995].

RREA spectrum



Assuming a TGF source at 15 km, the RREA spectra at satellite altitude matches RHESSI averaged TGF spectrum [*Dwyer and Smith*, GRL, 32, L22804, 2005].

High-energy AGILE anomalous spectrum



Calculated spectrum at satellite altitude. Circles with error bars are reproduced from *Tavani et al.* [Phys. Rev. Lett., 106, 018501, 2011] measurements.

Stepped leader propagation

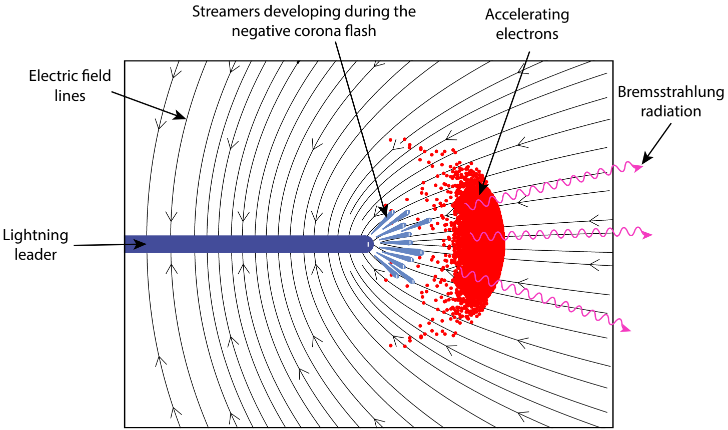
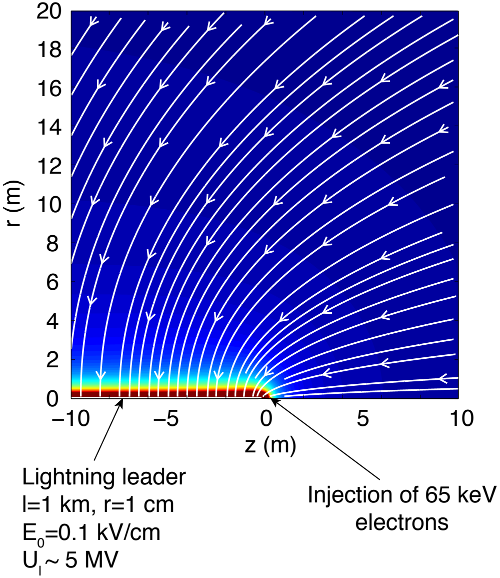
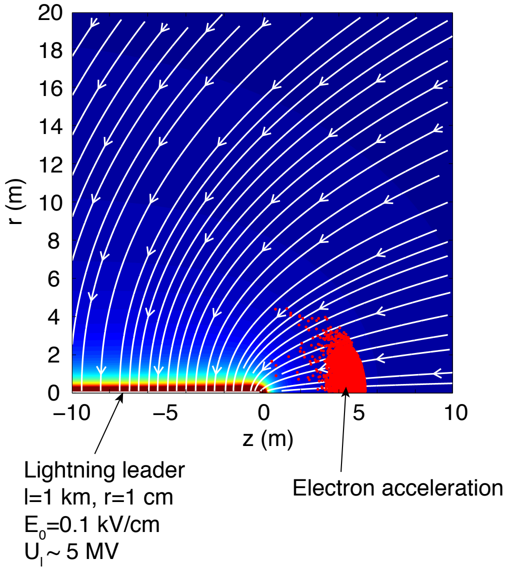


Illustration of the production of thermal runaway electrons and their acceleration in the lightning leader field during the negative corona flash process.

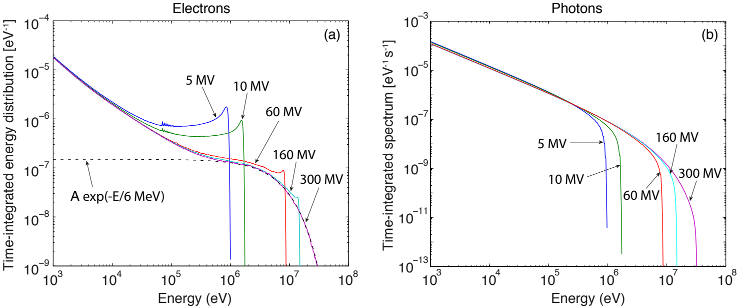
Electric field produced during the negative corona flash of a stepping leader



Electron acceleration in the electric field produced during the negative corona flash of a stepping leader

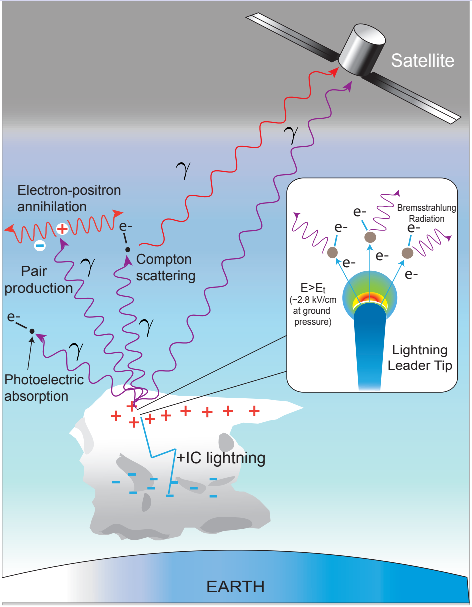


Time-integrated electron and photon distributions at the source



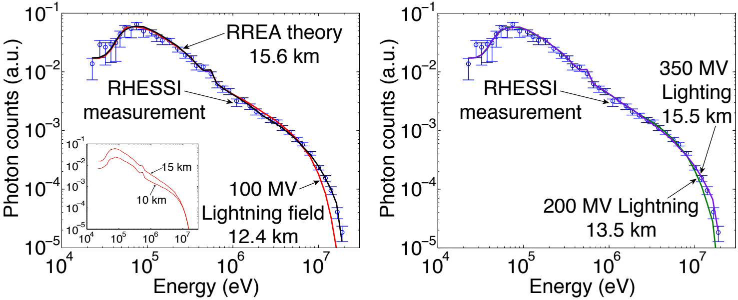
- Potential drop in front of the leader tip: $U_l = E_{amb} L/2$, where $E_{amb} \simeq 0.1$ kV/cm, 0.1 kV/cm, 0.6 kV/cm, 0.8 kV/cm, and 1 kV/cm, and $L \simeq 1$ km, 2 km, 2 km, 4 km, and 6 km are taken to construct potential drops of 5 MV, 10 MV, 60 MV, 160 MV, and 300 MV, respectively.
- The bremsstrahlung emission is simulated using the analytical bremsstrahlung differential cross section $\frac{d\sigma_\gamma}{d\varepsilon_\gamma}(\varepsilon, \varepsilon_\gamma)$ from [*Heitler*, 1954, p. 249].

Monte Carlo model to simulate photon transport



Credit: Wei Xu.

Source altitude determination and comparison to RHESSI measurements



RHESSI data are reproduced from [*Dwyer and Smith*, GRL, 32, L22804, 2005].
The detector response matrix was taken from
`http://scipp.ucsc.edu/~dsmith/tgflib_public/data/`
[*Xu et al.*, GRL, 39, L08801, 2012]

Fluence at satellite altitude

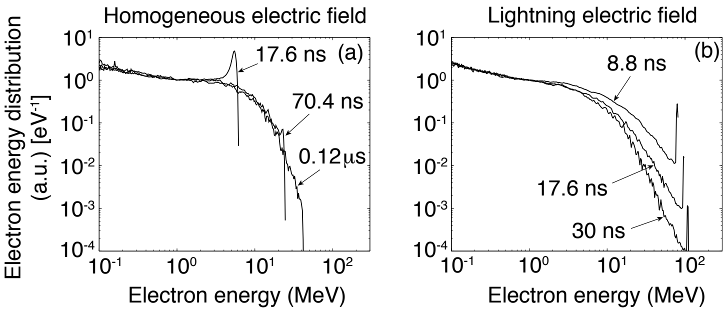
- The number of photons reaching satellite altitude ($\sim$500 km) depends mainly on the number of photons at the source, the source altitude, and the source photon spectrum.
- Using the Monte Carlo model of photon transport through the atmosphere, one obtains the predicted TGF fluence at an altitude of 500 km and a radial distance of 200 km from the source:

Potential drop	Fluence
5 MV	9×10^{-11} ph/cm^2
10 MV	5×10^{-9} ph/cm^2
60 MV	1.5×10^{-4} ph/cm^2
160 MV	0.01 ph/cm^2
300 MV	0.6 ph/cm^2

Number of photons with energy $>$10 keV at the source calculated from a reference of 10^{11} in a 5 MV leader case [*Schaal et al.*, JGR, 117, D15201, 2012; *Xu et al.*, GRL, 41, 7406, 2014].

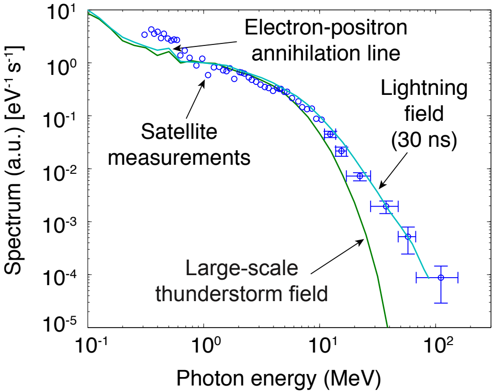
$\Rightarrow$ TGFs detected by satellites represent only a small fraction of a much larger distribution [see *Østgaard et al.*, JGR, 117, A03327, 2012].

Non-equilibrium features



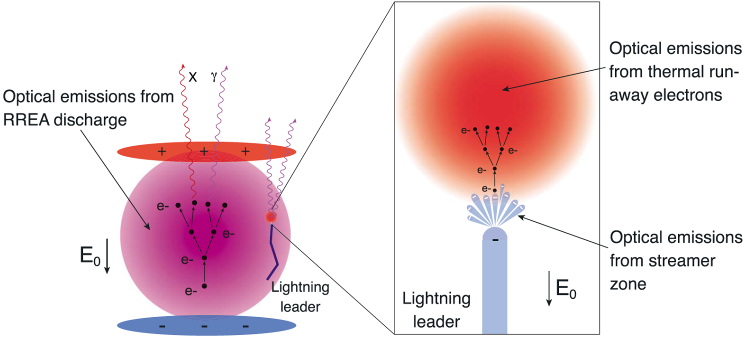
Panel (a): Homogeneous electric field 12.5 kV/cm. Panel (b): Inhomogeneous electric field produced by a 350 MV stepping lightning leader.

Non steady state lightning-produced TGF spectrum



Calculated spectrum at satellite altitude. Circles with error bars are reproduced from *Tavani et al.* [Phys. Rev. Lett., 106, 018501, 2011] measurements.

Optical emissions associated with TGFs



RREA in thunderstorm, large-scale homogeneous electric field

Thermal runaway electrons in the leader field

Illustration of optical emissions produced by two TGF production mechanisms [*Xu et al.*, JGR, 120, 1355, 2015, Figure 1].

Optical emissions associated with TGFs

Table 2. Intensity of Optical Emissions from $2PN_2$ (Column 3) and $1NN_2^+$ (Column 4) in Rayleighs and Intensity Ratio Between $2PN_2$ and $1NN_2^+$ (Column 5) in the Visible Range With Wavelengths Between 390 nm and 700 nm for Different Acceleration Processes (Column 1) With Different Characteristic Sizes (Column 2) Calculated at Ground Level

	Radius (m)	$2PN_2$ (R)	$1NN_2^+$ (R)	$\frac{2PN_2}{1NN_2^+}$
RREA (4.3 kV/cm)	1000	8.99×10^8	1.22×10^9	0.74
RREA (12.5 kV/cm)	1000	1.70×10^9	1.55×10^9	1.10
RREA (18.8 kV/cm)	1000	6.63×10^9	1.31×10^9	5.06
Thermal runaway electrons	50	8.28×10^{11}	5.23×10^{11}	1.58
Streamer zone	40	6.83×10^{10}	6.75×10^8	101.19

[*Xu et al.*, JGR, 120, 1355, 2015, Table 2].

Outlook

- Two main models can explain TGFs (large-scale RREAs and +IC lightning).
- Theoretical predictions on spectra, fluences, optical emissions, radio emissions, time dynamics (lightcurves), and accompanied electrical in-cloud activity, must be used to discriminate between those models.
- Need for faster instruments to reduce deadtime and pile-up.
- ASIM (ESA) and TARANIS (CNES).
- Need for observations at higher energies (up to 100 MeV) to confirm or invalidate AGILE high-energy anomalous spectrum.

Thank you for your attention.

This work is supported by the French space agency (CNES) as part of the TARANIS space mission.