Electron Acceleration Mechanisms in Thunderstorms

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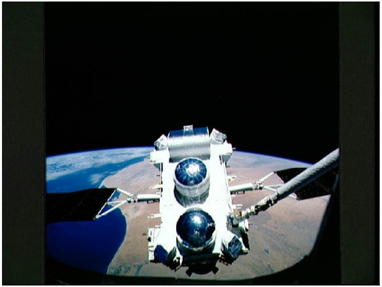
Discovery of Terrestrial Gamma ray Flashes

- CGRO's mission: to observe celestial gamma-ray sources.
- CGRO had four instruments that covered an unprecedented six decades of the electromagnetic spectrum, from $\sim$20 keV to 30 GeV.



CGRO with its solar array panels deployed is grappled by the remote manipulator system (RMS) during STS-37 systems checkout. Credit: NASA.

- The Burst and Transient Source Experiment (BATSE) detector modules are located on the 8 corners of CGRO.

Introduction

- In May 1994, Dr. Fishman and collaborators report the discovery of unexplained gamma-ray flashes of atmospheric origin (>300 keV), that we know today as "Terrestrial Gamma-ray Flashes" (TGFs).

- The gamma-ray flashes are observed to be correlated with thunderstorm activity.

Discovery of Intense Gamma-Ray Flashes of Atmospheric Origin

G. J. Fishman, P. N. Bhat,* R. Mallozzi, J. M. Horack, T. Koshut, C. Kouveliotou, G. N. Pendleton, C. A. Meegan, R. B. Wilson, W. S. Paciesas, S. J. Goodman, H. J. Christian

Detectors aboard the Compton Gamma Ray Observatory have observed an unexplained terrestrial phenomenon: brief, intense flashes of gamma rays. These flashes must originate in the atmosphere at altitudes above at least 30 kilometers in order to escape atmospheric absorption and reach the orbiting detectors. At least a dozen such events have been detected over the past 2 years. The photon spectra from the events are very hard (peaking in the high-energy portion of the spectrum) and are consistent with bremsstrahlung emission from energetic (million–electron volt) electrons. The most likely origin of these high-energy electrons, although speculative at this time, is a rare type of high-altitude electrical discharge above thunderstorm regions.

[*Fishman et al.*, Science, 264, 1313, 1994]

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Terrestrial Gamma-ray Flashes (TGFs)

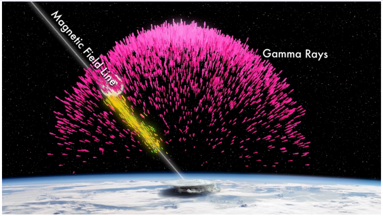
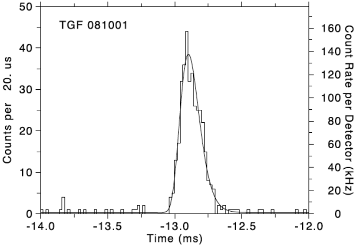


Illustration of a TGF. Credit: NASA/Goddard Space Flight Center.



Example of a TGF detected by Fermi-GBM [*Briggs et al.,* JGR, 115, A07323, 2010].

- Typical max. energy: $\sim$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 $\sim$100 μs [e.g., *Fishman et al.*, J. Geophys. Res., 116, A07304, 2011; *Marisaldi et al.*, Geophys. Res. Lett., 42, 9481, 2015].
- Typical fluence: $\gtrsim$0.5 photon/cm^2 when observed from low-orbit.
  - The maximum TGF fluence is yet to be established (due to deadtime, pile-up, etc.).

Terrestrial Gamma-ray Flashes (TGFs)

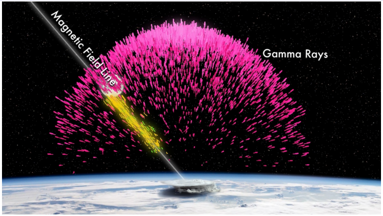
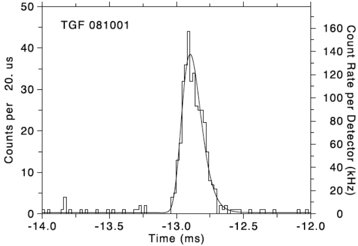


Illustration of a TGF. Credit: NASA/Goddard Space Flight Center.



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What is the origin of these energetic radiation bursts?

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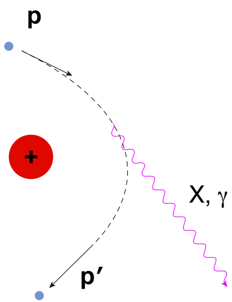
- TGF spectrum is consistent with bremsstrahlung emission (or "braking radiation") from energetic electrons.



Bremsstrahlung emission process.

- Production of energetic electrons in the atmosphere?

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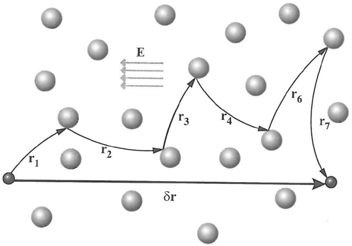
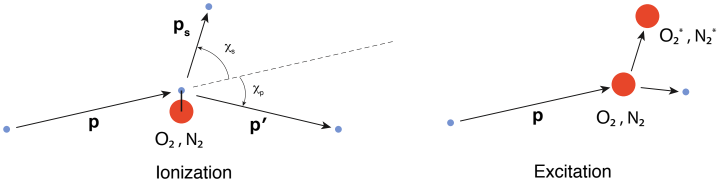
- In discharges in air at atmospheric pressure electrons usually do not gain energies much higher than 10 eV ($k_B T_{amb} \simeq 0.026$ eV).
- Lightning can heat the air up to $\sim$30,000 K, corresponding to $\sim$2.6 eV.
- On average, electrons “feel” a friction force along with the electric force. The friction force depends on the nature of collisions that electrons experience, and therefore on the energy of the electrons.



Electrons propagating in a gas where an electric field is applied [*Rax*, 2005, Figure 2.4].

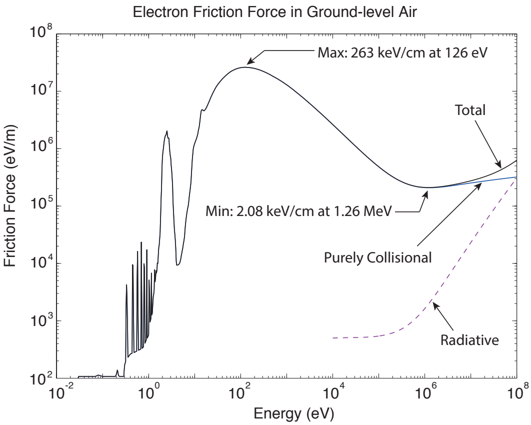
Various collisional processes



- A collisional process j is associated with a frequency $\nu_j(\varepsilon)$ and a loss of energy $\delta\varepsilon_j(\varepsilon)$,
- The frequency is related to the cross section $\sigma_j(\varepsilon)$ through $\nu_j(\varepsilon) = N\sigma_j(\varepsilon)v(\varepsilon)$, where N is the density of the molecular gas and v is the velocity of the electron. The mean free path is $\lambda_j(\varepsilon) = (N\sigma_j(\varepsilon))^{-1}$.
- The total energy loss per unit length over all collisions can be calculated through:

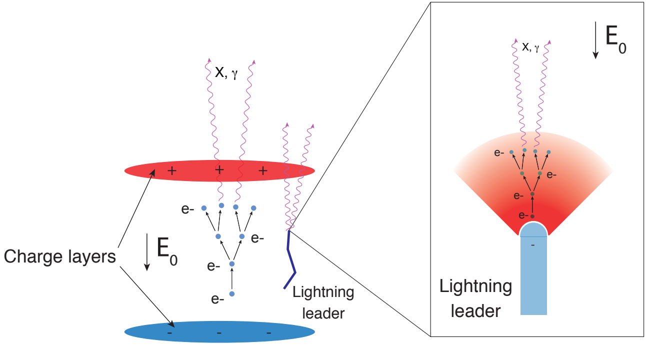
$$F_D(\varepsilon) = \sum_j \frac{\delta\varepsilon_j(\varepsilon)}{\lambda_j(\varepsilon)} = \sum_j N\sigma_j\delta\varepsilon_j(\varepsilon) \quad (1)$$

Electron stopping power



- The dynamic friction force represents the energy loss by one electron per meter (air, ground level atmospheric pressure).

Two theories to explain TGFs

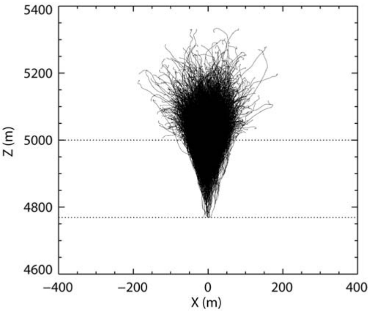


RREA in thunderstorm weak electric field
[e.g., *Dwyer*, JGR, 113, D10103, 2008]

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

Relativistic Runaway Electron Avalanches

seeded by energetic electrons produced by cosmic ray air showers alone



[*Dwyer et al.,* J. Geophys. Res., 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.* [J. Geophys. Res., 113, D10103, 2008] demonstrated that TGFs cannot be produced by relativistic runaway electron avalanches acting on natural background radiation or extensive air showers alone.

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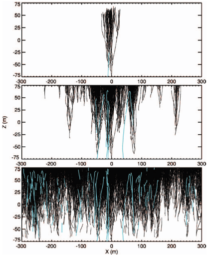

[*Dwyer*, Phys. Plasmas, 14, 042901, 2007, Figure 2].

- 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*, J. Geophys. Res., 117, A02308, 2012; *Liu and Dwyer*, J. Geophys. Res., 118, 2359, 2013].
- Feedback requires electric fields >4 kV/cm ($\times N/N_0$) extending over several kilometers [e.g., *Skeltved et al.*, J. Geophys. Res., 119, 9174, 2014], while measurements show ambient electric fields <2 kV/cm ($\times N/N_0$) in thunderclouds [e.g., *Marshall et al.,* J. Geophys. Res., 100, 7097, 1995].

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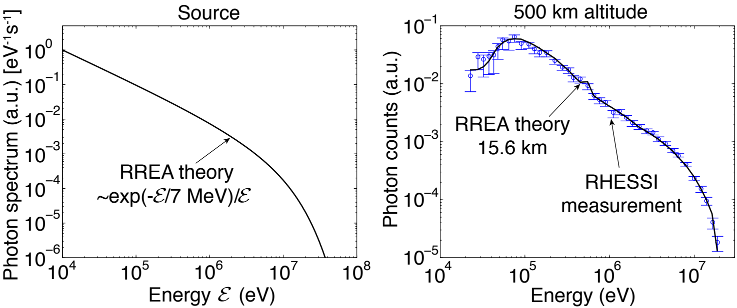
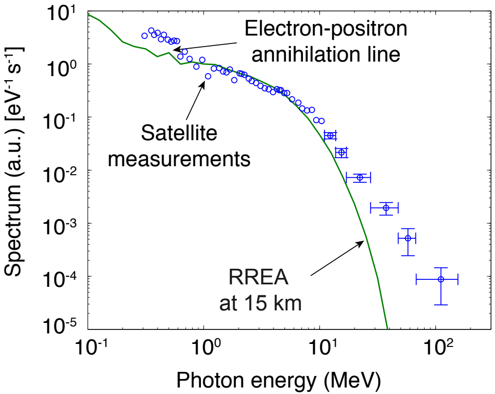
RREA spectrum



Assuming a TGF source at 15 km, the RREA spectra at satellite altitude matches RHESSI averaged TGF spectrum [*Dwyer and Smith*, Geophys. Res. Lett., 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.

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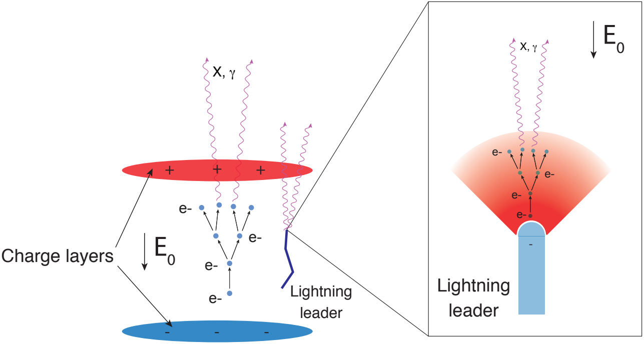
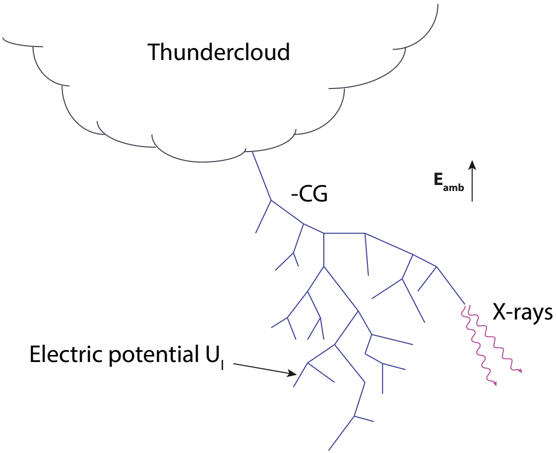
Two theories to explain TGFs



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]

X-ray bursts from -CG stepped leaders



X-ray bursts have been detected in association with negative cloud-to-ground (-CG) lightning leader steps [e.g., *Moore et al.*, Geophys. Res. Lett., 28, 2141, 2001; *Dwyer et al.*, Geophys. Res. Lett., 32, L01803, 2005].

Leader stepping and energetic electrons

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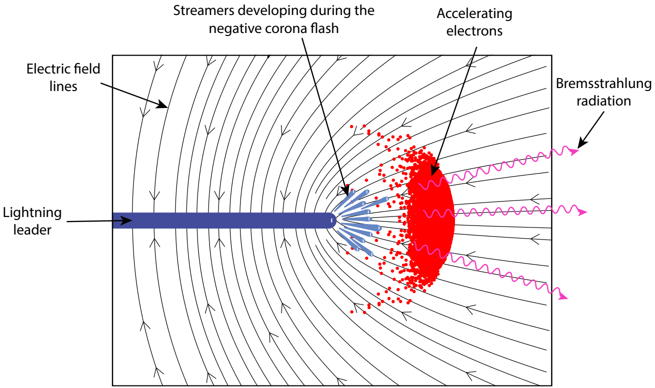

- High electric fields in streamer heads producing thermal runaway electrons.
- Acceleration of runaway electrons in the lightning leader electric field.

Model formulation

In this study, we use three different numerical models:

- The method of moments [*Balanis*, Advanced Engineering Electromagnetics, 1989, p. 670] to solve for the charge distribution that keeps the electric potential constant in the leader (perfect conductor) under a given ambient electric field. From the charge distribution obtained, we find the electric field produced by the leader when no streamer zone is yet present.
- A relativistic Monte Carlo model simulating the propagation of electrons through air under a given electric field from sub-eV to GeVs [*Celestin and Pasko*, 2011]. Simulations have been performed in air (80% N_2 + 20% O_2) at ground conditions with density N=2.688 $\times$ 10^{25} m^{-3}.
- A Monte Carlo model simulating photon transport through the atmosphere based on that described by *Østgaard et al.* [J. Geophys. Res., 113, A02307, 2008]. Three main collision types for photons with energies $>$10 keV are considered: photoelectric absorption (main process for energies up to $\sim$30 keV), Compton scattering (main process from $\sim$30 keV to $\sim$30 MeV), and electron-positron pair production (main process $>$30 MeV).

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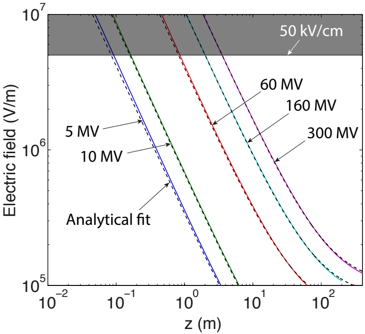
Leader electric field in five cases



Electric field as a function of distance from the leader tip. The dashed lines represent analytical fits of the numerical solutions. Electric fields with amplitudes greater than 50 kV/cm are not considered in this study (grey area) as they could only be present on very short timescales. Reproduced from [*Celestin et al.*, J. Geophys. Res., 120, 10712, 2015].

- 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 used to construct potential drops of 5 MV, 10 MV, 60 MV, 160 MV, and 300 MV, respectively.

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

Energetic electrons ($>$10 keV) dynamics under the electric field of a 5 MV lightning leader during a negative corona flash. Calculation performed in air at ground level density.

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

Energetic electrons (>10 keV) dynamics under the electric field of a 300 MV lightning leader during a negative corona flash. Calculation performed in air at ground level density.

Photon transport

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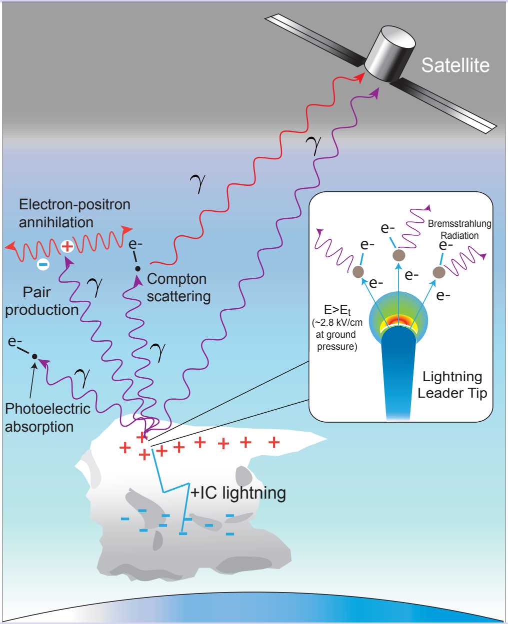
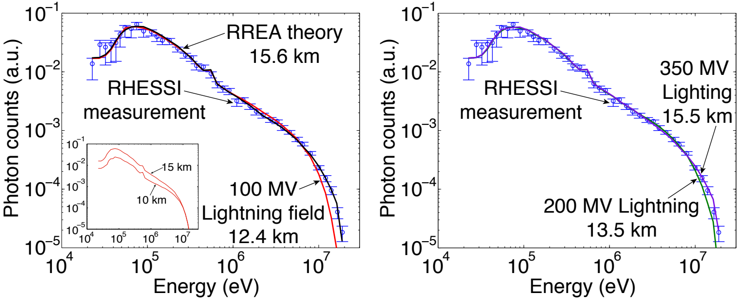


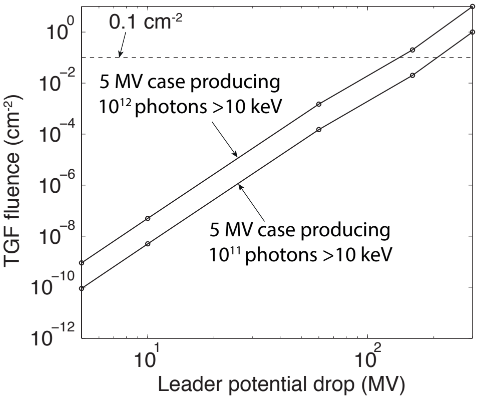
Credit: Wei Xu.

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]

Photon fluence observed from space



Calculated TGF fluence as a function of the potential drop formed by the causative lightning leader at an altitude of 500 km and a radial distance of 200 km from the source. Reproduced from [*Celestin et al.*, J. Geophys. Res., 120, 10712, 2015].

Optical emissions associated with TGFs

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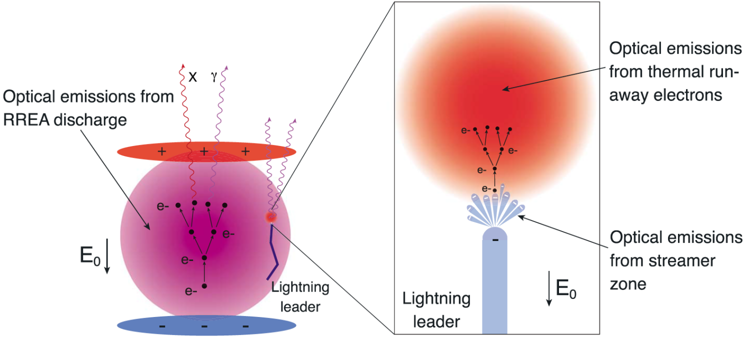

RREA in thunderstorm, large-scale homogeneous electric field

Thermal runaway electrons in the leader field

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

Optical emissions associated with TGFs

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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.*, J. Geophys. Res., 120, 1355, 2015, Table 2].

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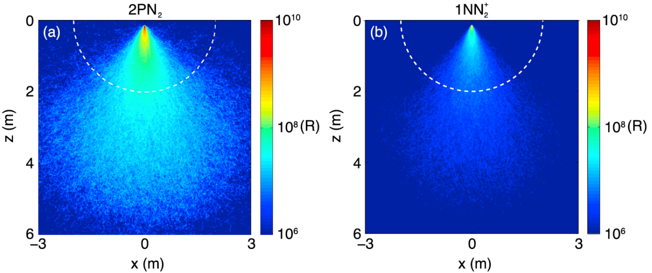


Figure 2. Optical emissions of (a) $2PN_2$ and (b) $1NN_2^+$ resulting from continuous emission of thermal runaway electrons into the 5 MV lightning leader field during the negative corona flash stage, considering an emission rate of 10^{17} s^{-1} [*Schaal et al.*, 2012]. The results are calculated using a convolution technique at ground-level atmospheric density. The dashed lines represent the theoretical size of the associated streamer zone.

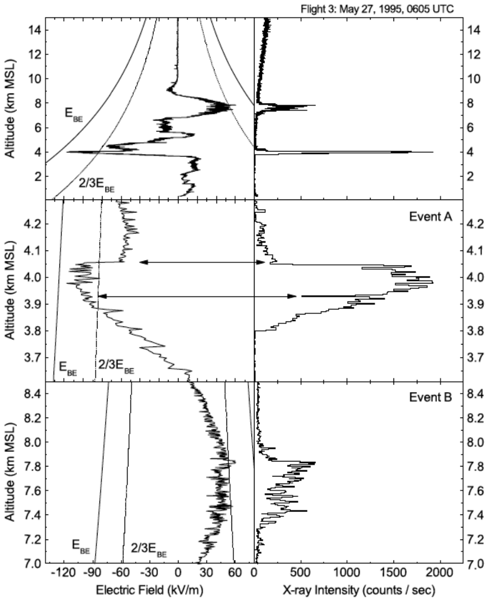
[*Xu et al.*, Geophys. Res. Lett., 42, 5610, 2015, Figure 2].

Gamma ray glows

- Gamma ray glows are enhancements of the background radiation occurring in thunderclouds.
- Similar spectrum as TGFs but orders of magnitude less bright [e.g., *Kelley et al.*, Nature Comm., 6, 7845, 2015].
- Observations in stratiform regions (high electric fields) of mesoscale convective systems.
- Observations using airplane [*McCarthy and Parks*, Geophys. Res. Lett. 12, 393, 1985; *Kelley et al.*, 2015] and balloons [*Eack et al.*, J. Geophys. Res., 101, 29637, 1996].

Balloon observations

[Eack and Beasley, J. Geophys. Res., 120, 6887, 2015, Figure 5]



Airplane (ADELE) observations

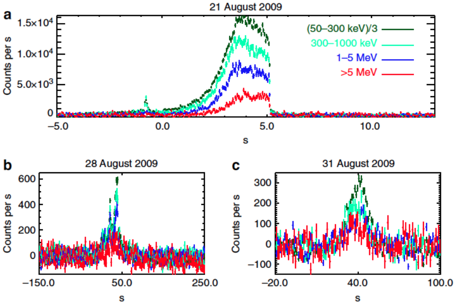


Figure 1 | Time profile of three ADELE glows. The two large plastic detector data have been summed and background subtracted. The lowest channel (dark green) is divided by three to show the higher energy channels more clearly. (**a**) The brightest glow on 21 August 2009, which had an abrupt ending; (**b**,**c**) two other more typical glows in which the instrument probably passed by but not through the avalanches.

Reproduced from [*Kelley et al.*, Nature Comm., 6, 7845, 2015, Figure 1].

- Timescale believed to be due to the duration for the aircraft to fly through.

Thunderstorm Ground Enhancements (TGEs)

- TGEs are are long duration ($>$1 s) enhancements of the background radiation observed from the ground during stormy weather.
- They are believed to be produced by presence of the lower positive charge region in a thunderstorm [*Chilingarian et al.*, Atm. Res., 114-115, 1-16, 2012].
- Most TGEs are produced by acceleration of secondary cosmic rays (modification of spectrum (MOS)) while some intense TGEs are produced by RREAs [*Chilingarian et al.*, EPL, 106, 59001, 2014].

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- Since the 1990s, a new field of research named High-Energy Atmospheric Physics has emerged [*Dwyer et al.*, Space Sci. Rev., 173, 133, 2012].
- The physical systems covered by this new field are based on the *runaway acceleration processes*.
- Various phenomena have been observed such as TGFs, glows, and TGEs.
- Production mechanisms for some of these phenomena are up for debate.
- The first space missions designed for the study of TGFs and related phenomena will be launched in the coming years: TARANIS (CNES) and ASIM (ESA).
- Recently, the study of cosmic rays has brought a new exciting way to probe thunderstorms: *Schellart et al.* [Phys. Rev. Lett., 114, 165001, 2015] have studied the intensity and polarization patterns of air showers using LOFAR and deduce one component of the large-scale field inside the thunderstorms!

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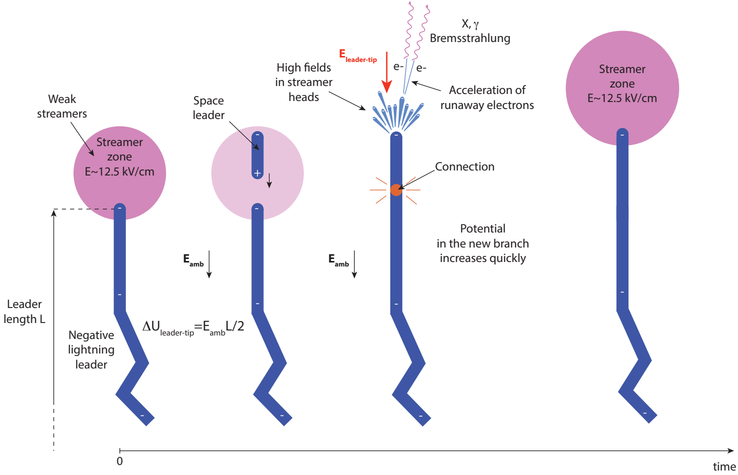
Thank you for your attention.

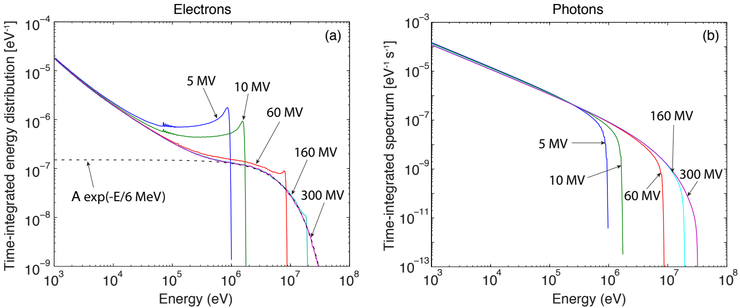
This work is supported by the French space agency (CNES). Part of the simulation results presented in this talk has been obtained using the computer cluster at the Centre de Calcul Scientifique en région Centre-Val de Loire (CCSC).

Leader stepping and energetic electrons



[e.g., *Moss et al.*, J. Geophys. Res., 111, A02307, 2006; *Celestin and Pasko*, J. Geophys. Res., 116, A03315, 2011]

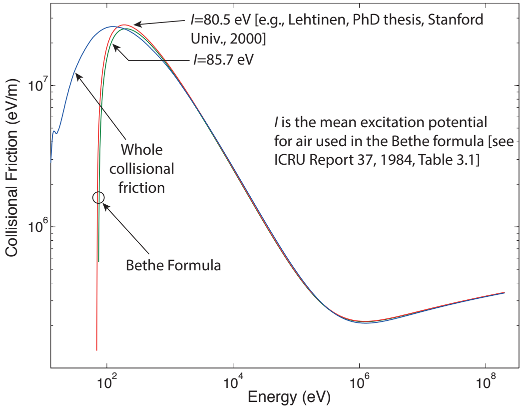
Time-integrated electron and photon distributions at the source



(a) Time-integrated electron energy distribution functions for each lightning leader potential drop magnitude used in the present study. (b) Corresponding bremsstrahlung photon spectra at the source location. Reproduced from [*Celestin et al.*, J. Geophys. Res., 120, 10712, 2015].

- The bremsstrahlung emission spectrum is calculated using the analytical bremsstrahlung differential cross section $\frac{d\sigma_\gamma}{d\varepsilon_\gamma}(\varepsilon, \varepsilon_\gamma)$ from [*Lehtinen*, PhD thesis, Stanford University, 2000, pp. 45-49].
- 5MV -CG lightning stepped leaders would produce X-ray spectra similar to observational results of *Schaal et al.* [J. Geophys. Res., 117, D1520, 2012] (see [*Xu et al.*, Geophys. Res. Lett., 41, 7406, 2014]).

Electron stopping power: Bethe formula



- The dynamic friction force represents the energy loss by one electron per meter (air, ground level atmospheric pressure).

Number of high-energy electrons at the source

- The number of thermal runaway electrons N_{th} initially produced by streamers during the negative corona flash is supposed to be proportional to the number of streamers in the streamer zone N_{s}, which is theoretically proportional to the square of the potential drop U_{l} in the leader tip region [*Celestin and Pasko*, 2011]:

$$N_{\mathrm{th}} = \xi N_{\mathrm{s}} = \xi \frac{\pi \varepsilon_0 U_{\mathrm{l}}^2}{2 E_{\mathrm{s}}^- q_{\mathrm{s}}} \tag{2}$$

  where ξ is a proportionality constant, ε_0 is the permittivity of free space, $q_{\mathrm{s}} \simeq 1$ nC is the typical charge in the streamer head [*Bazelyan and Raizer*, Lightning Physics and Lightning Protection, 2000, pp. 69–71], and E_{s}^- is the critical field for stable propagation of negative streamer.

- We have recently found [*Xu et al.*, Geophys. Res. Lett., 41, 7406, 2014] that 5 MV -CG lightning stepped leaders would produce X-ray spectra similar to observational results of *Schaal et al.* [J. Geophys. Res., 117, D1520, 2012] in terms of general shape and spectral hardness, and this potential drop is also consistent with the size and electric charge of streamer zones inferred from X-ray observations obtained by *Schaal et al.* [J. Geophys. Res., 119, 982, 2014].

Number of high-energy photons at the source

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- We use a reference of 10^{11}–10^{12} photons with energy $>$10 keV produced in the 5 MV leader case, which corresponds to the observation-based analyses of X-rays produced by negative cloud-to-ground discharges [e.g., *Saleh et al.*, J. Geophys. Res., 114, D17210, 2009; *Dwyer et al.*, J. Geophys. Res., 115, D09206, 2010; *Schaal et al.*, J. Geophys. Res., 117, D15201, 2012].

Leader potential drop	Total number of photons ($>$10 keV)
5 MV	$10^{11} - 10^{12}$
10 MV	$10^{12} - 10^{13}$
60 MV	$6 \times 10^{14} - 6 \times 10^{15}$
160 MV	$4 \times 10^{16} - 4 \times 10^{17}$
300 MV	$2 \times 10^{18} - 2 \times 10^{19}$

Number of photons with energy $>$10 keV at the source.

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Impact of the production altitude / similarity laws

- The electric field close to the leader along the axis is well reproduced by:

$$E(z) \simeq \frac{\alpha U_l}{z} + E_0 \tag{3}$$

where $\alpha \simeq 0.066$ in SI units.

- The work done by the electric field on one runaway electron is:

$$G = \int_{z_1}^{z_2} q_e E(z) dz \simeq q_e \alpha U_l \ln\left(\frac{\mathrm{E}_1 - \mathrm{E}_0}{E_2 - E_0}\right) + q_e E_0 (z_2 - z_1) \tag{4}$$

where $E_1 = 50$ kV/cm $\times N/N_0$ and $E_2 = 2.8$ kV/cm $\times N/N_0$, hence $z_2 - z_1 \propto N_0/N$. If one has $E_0 \propto N/N_0$, G is invariant.

- The energy loss caused by collisions can be estimated approximately for minimum ionizing electrons ($\gtrsim$200 keV):

$$L = \int_{z_1}^{z_2} F(\varepsilon) dz \simeq F_{\mathrm{min}}(z_2 - z_1) \tag{5}$$

where F is the dynamic friction and ε is the electron energy. Since $F \propto N/N_0$, L is invariant.

Impact of the production altitude / similarity laws

- The ratio of the air density at ground level to that at 12 km altitude is $\sim$4.2.
- From the shape of the electric field produced by the leader, it can be shown that for a given leader potential drop U_l, the energy gain is approximately invariant.
- This is in general agreement with simulation results obtained at an altitude of 12 km.
- The propagation length of runaway electrons scales as $\sim N_0/N$. In the 300 MV leader case, the propagation of runaway electrons would be $\sim$1.4 km at 12 km altitude.
- The number of streamers scales as $\sim N_0/N$.

Production of extreme potential drops by +IC negative lightning leaders

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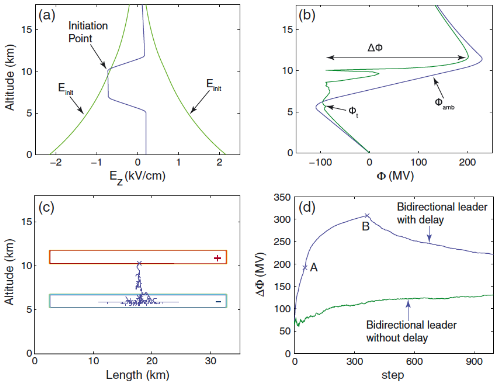
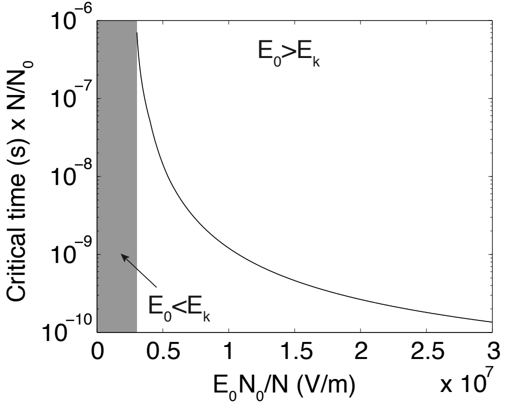


Figure 1. Case of a +IC lightning. (a) Ambient electric field distribution along the axis of the simulation domain. (b) Potential distribution along the axis of the simulation domain before the lightning development (ϕ_{amb}) and at the simulation step when the potential difference between the negative leader tip and the ambient potential ($\Delta\phi$) is maximum (ϕ_{t}) in the case of a delay in the negative leader propagation. (c) Cross section of the lightning discharge structure at the step when the potential difference between the negative leader tip and the ambient potential ($\Delta\phi$) is maximum in the case of a delay of the negative leader propagation. (d) Potential difference between the negative leader tip and the ambient potential ($\Delta\phi$) at every simulation step. Point A denotes the start of the horizontal development of the positive leader, while point B denotes the initiation point of the negative leader.

Reproduced from [*Mallios et al.*, J. Geophys. Res., 118, 912, 2013, Figure 1].

Sustainable electric field over a given time



Maximum time over which a given electric field E_0 can be sustained.

Runaway electrons amplification in front of the leader tip

Electron Acceleration Mechanisms in Thunderstorms

Sebastien Celestin

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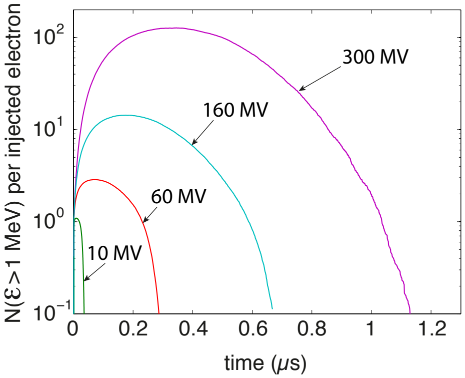
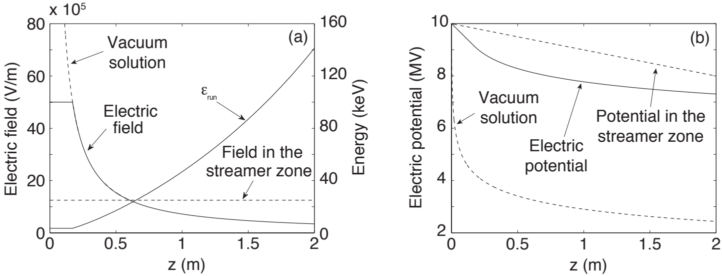


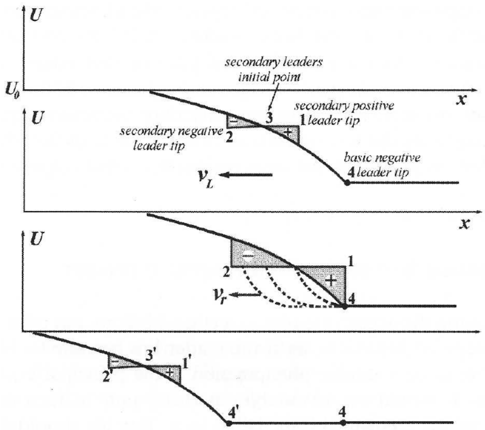
Number of electrons with energy >1 MeV with respect to time. This duration must be modulated by the negative corona flash duration as these results correspond to impulse responses. Reproduced from [*Celestin et al.*, J. Geophys. Res., 120, 10712, 2015].

Electric field and potential generated by the leader tip



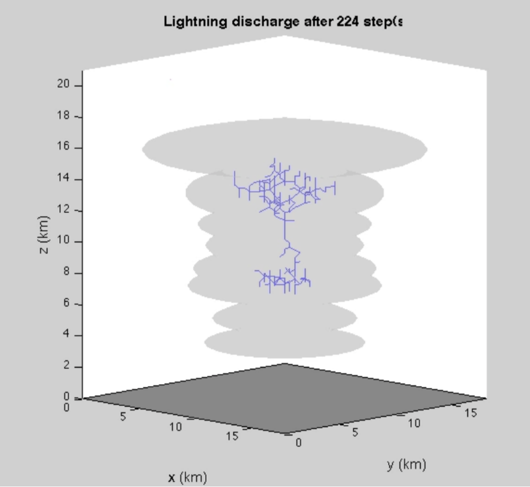
(a) Characteristic magnitude of the free space electric field calculated using the methods of moments produced by a perfectly conducting leader branch of 1 km length with a radius of 1 cm immersed in an ambient thundercloud electric field of 0.2 kV/cm. The corresponding minimum energy for thermal runaway electrons $\varepsilon_{\rm run}$ is also shown.

Potential drops in the leader tip during stepping



Potential distribution during stages of a step formation [*Bazelyan and Raizer*, Lightning Physics and Lightning Portection, IOP Publishing, 2000, Figure 4.22].

Extensive branching of the IC lightning - the end of the TGF



Simulation of an intra-cloud lightning [*Krehbiel et al.*, Nature Geosci., 1, 2008, Supplementary Information]. Intense branching of the upper part is responsible for the end of the high potential difference formed in the vicinity of negative leader tips.

Balloon observations

[Eack and Beasley, J. Geophys. Res., 120, 6887, 2015]

- Instrument: 50 mm $\times$ 2 mm NaI, three-channel (30-60, 60-90, and 90-120 keV) X-ray energy spectrum acquired 4 times per second.
- 10 to 1000 times normal background rate.
- Observations in stratiform regions (high electric fields) of MCSs.
- 5 flights: 3 with large increases of X-ray fluxes, 1 with weaker X-ray emissions, 1 without emission above normal background.

Airplane (ADELE) observations

- Instrument: Two 127 mm $\times$ 127 mm plastic scintillators, read out by discriminators with energy thresholds corresponding to roughly 50, 300 keV, 1, and 5 MeV. Counts are accumulated in 50 μs bins [Smith et al., J. Geophys. Res., 116, D20124, 2011].
- Observations close to thunderstorms as a safety precaution (breached once by accident)
  $\Rightarrow$ 21 August event.
- Altitude $\sim$14 km, electron flux in the source is $\sim$1000 s^{-1} cm^{-2}.