Relativistic and Streamer/Leader Processes

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Big picture

- Lightning initiation

  - Streamers are created (from hydrometeors?), propagate, and branch in high-field regions.

  - Streamer currents heat the air forming hot leader channels, i.e., via the streamer-to-leader transition.

- Lightning propagation

  - Leaders propagate large distances by creating streamers.

  - Streamer currents heat the air forming new hot leader channels…

- Attachment and return strokes, K-changes (i.e., dart leaders),….
- These processes produce field changes, electromagnetic waves, high-energy radiation, optical emissions, sound….

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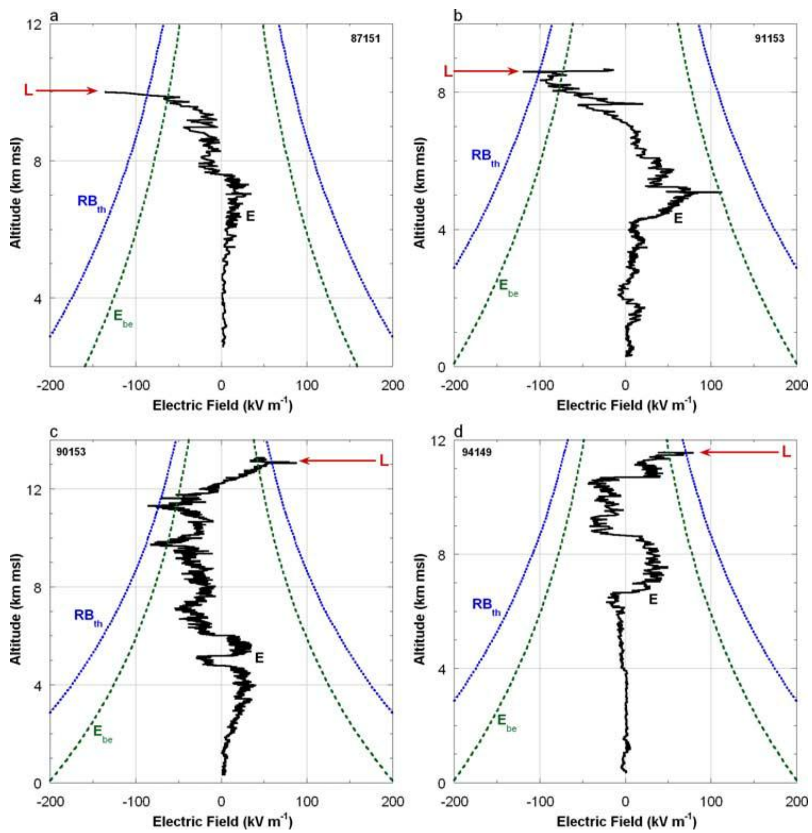
To model these steps, we need to know the thunderstorm electric fields!

Major Questions

- What electric fields are commonly produced inside thunderstorms and what electric fields are present during lightning initiation?
- What high-energy processes occur and how do these affect the electric fields?
- How does lightning initiate? In particular, when, where and how are the first leaders formed?
- How exactly does lightning propagate?
- What emissions are produced?

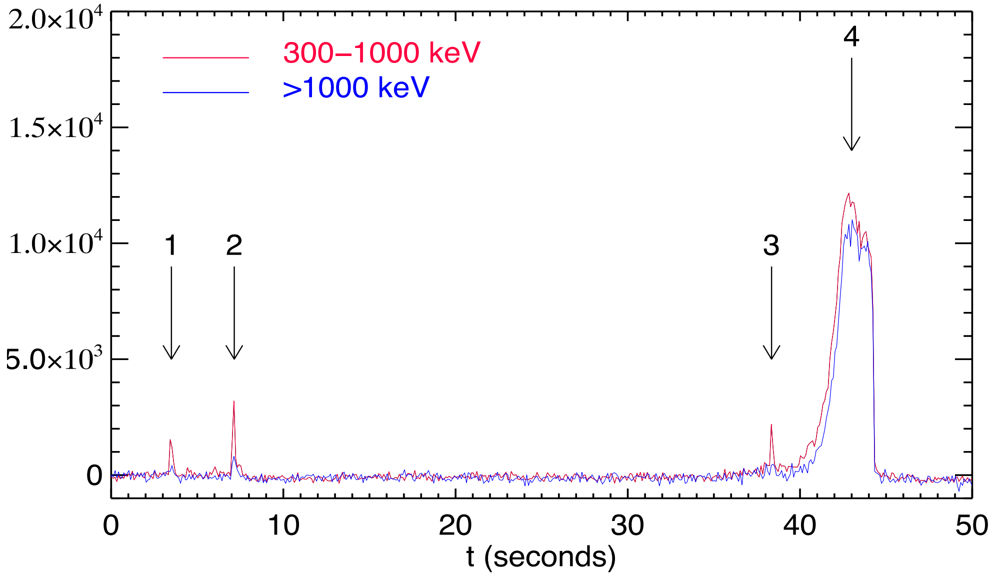
These are interconnected!

Electric fields inside thunderstorms

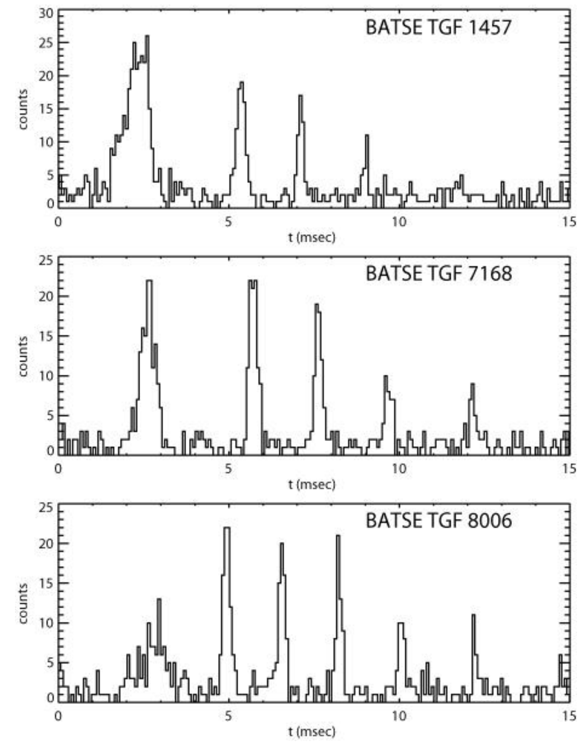


Four balloon soundings from Stolzenburg et al. (2007). For all 4 soundings the electric field strength rapidly increased, beginning a few seconds before the lightning, shown as red arrows. Also shown are the runaway electron avalanche threshold (labeled RB_{th}) and the so-called breakeven threshold for runaway electron propagation (labeled E_{be}), both as a functions of altitude.

Gamma-ray glows and Terrestrial Gamma-ray flashes (TGFs)

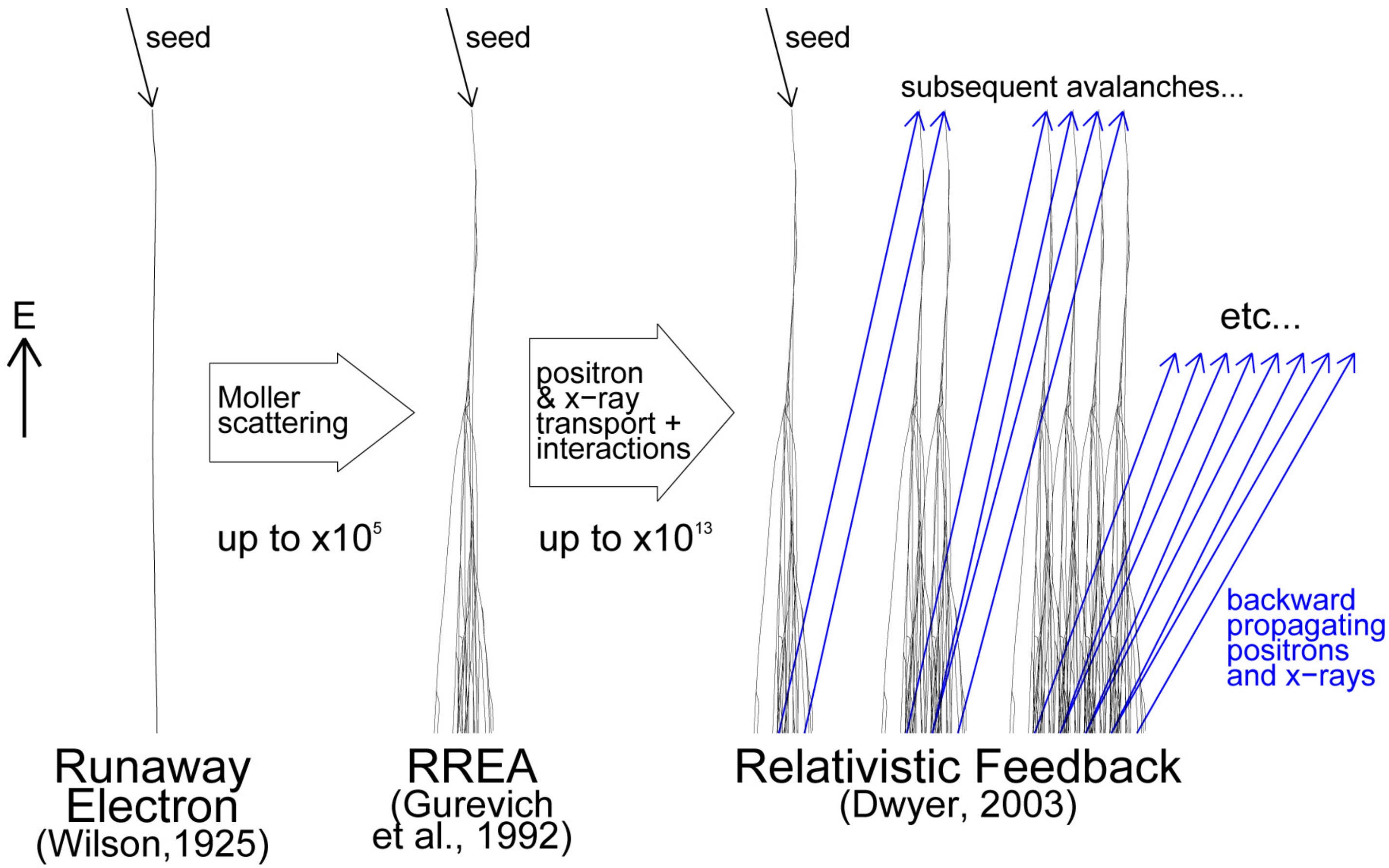


Four gamma-ray glows recorded by ADELE onboard a G-V aircraft inside a thunderstorm (from Dwyer et al. 2015).



Three multi-pulsed TGFs observed by CGRO/BATSE (from Dwyer 2012).

High-energy processes within thunderstorms

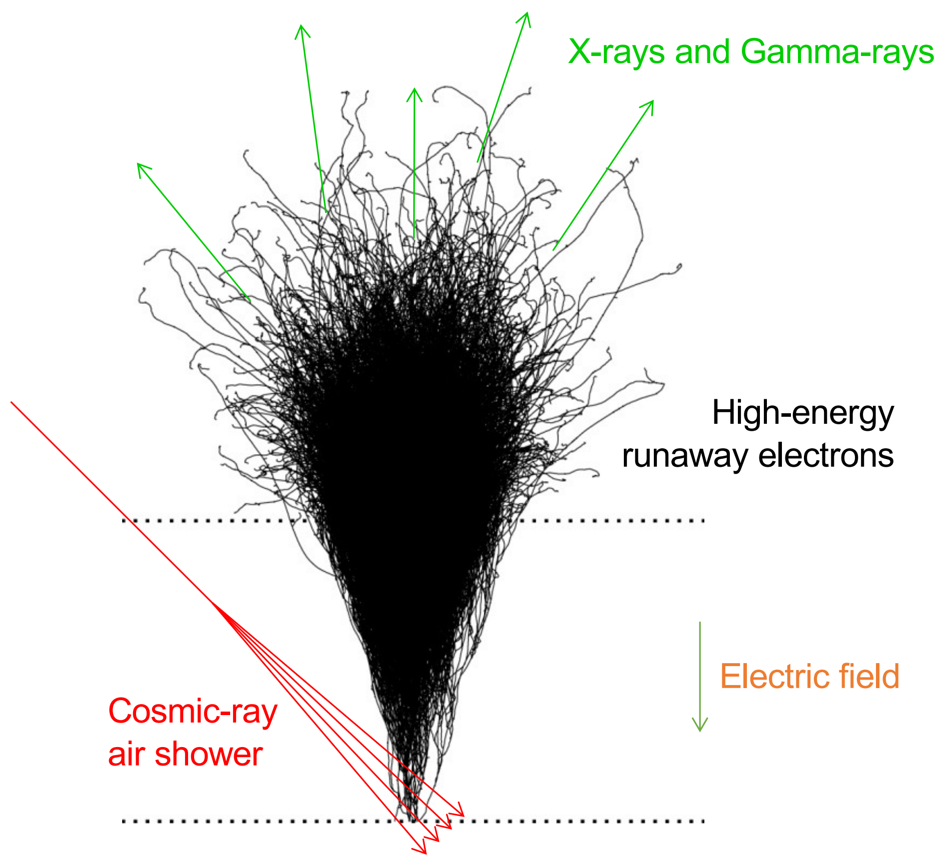


From Dwyer, Smith and Cummer (2012)

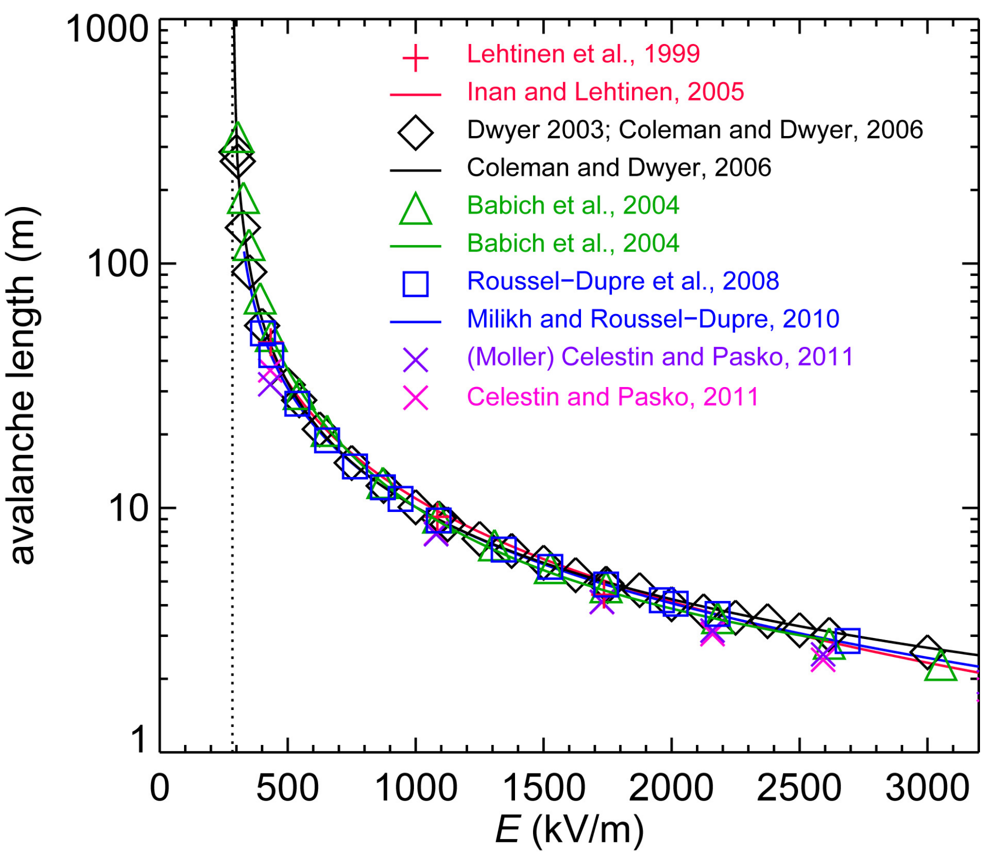
Monte Carlo Simulations

- The Runaway Electron Avalanche Model (REAM) is a code written specifically to simulate runaway electrons and relativistic feedback (e.g., Dwyer 2007).
- It agrees well (within 10%) with other codes include GEANT4, a standard MC code used to simulate high-energy particles, and custom-built codes such as GRanada Relativistic Runaway simulator (GRRR) and MC-PEPTITA (Sarria et al. 2018).
- REAM includes, in an accurate form, all the important interactions involving energetic electrons, positrons, x-rays and gamma-rays. These interactions include energy losses through ionization and atomic excitation, Møller scattering, elastic scattering, bremsstrahlung production of x-rays and gamma-rays and the subsequent propagation of the photons, including Rayleigh scattering, Compton scattering, photoelectric absorption and pair production. In addition, the simulation includes positron propagation (and annihilation) and the generation of energetic seed electrons via Bhabha scattering of positrons and Compton scattering, photoelectric absorption and pair-production of energetic photons.

Result of the REAM simulation showing a relativistic runaway electron avalanche (RREA)



Validating the codes



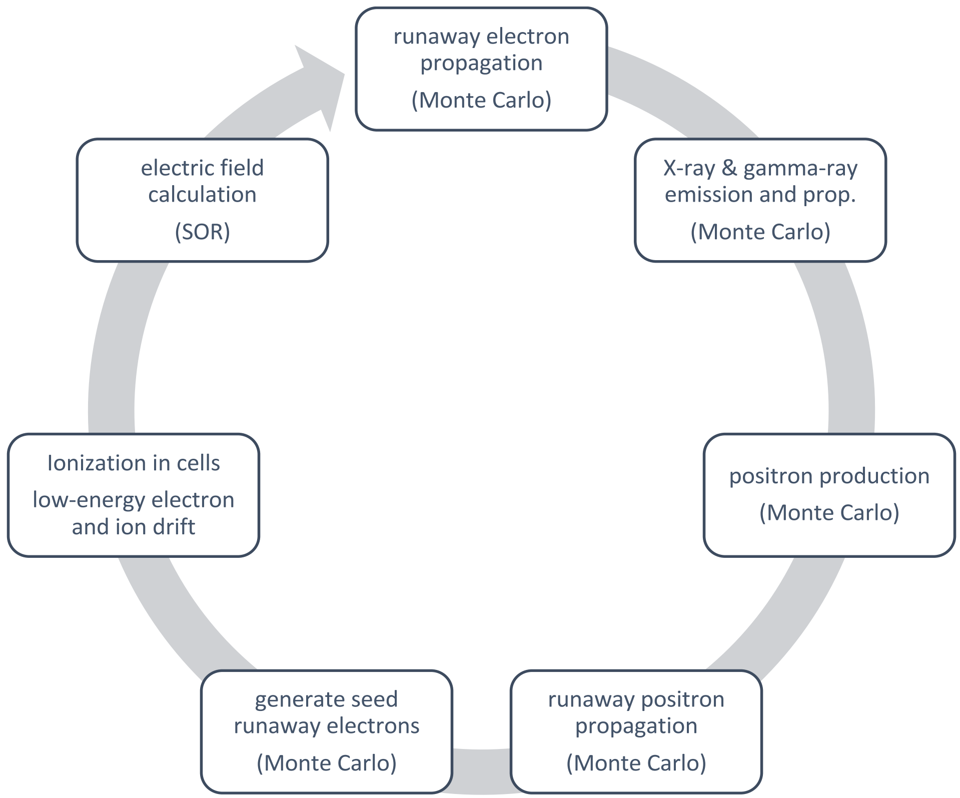
The codes generally agree on the behavior of the energetic particles.

Where differences occur is what background electric fields are assumed when implementing the simulations and what role lightning plays in the emissions.

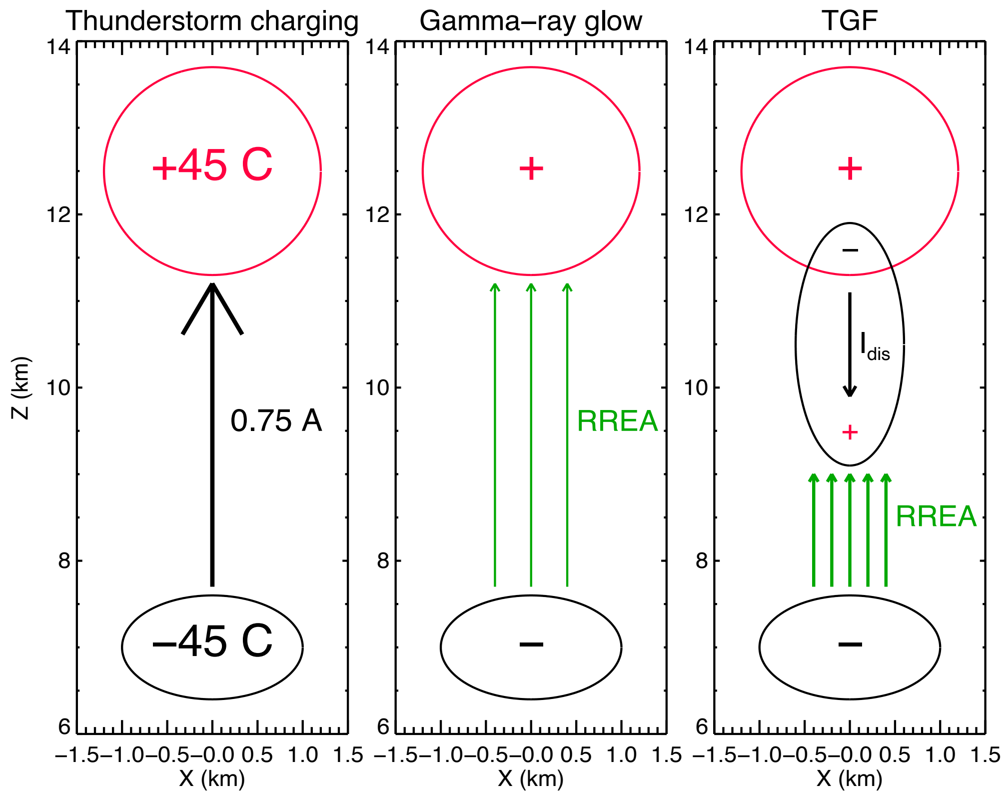
At present, not all codes self-consistently include the change in the electric field caused by the ionization from the high-energy particles.

From Dwyer, Smith and Cummer (2012)

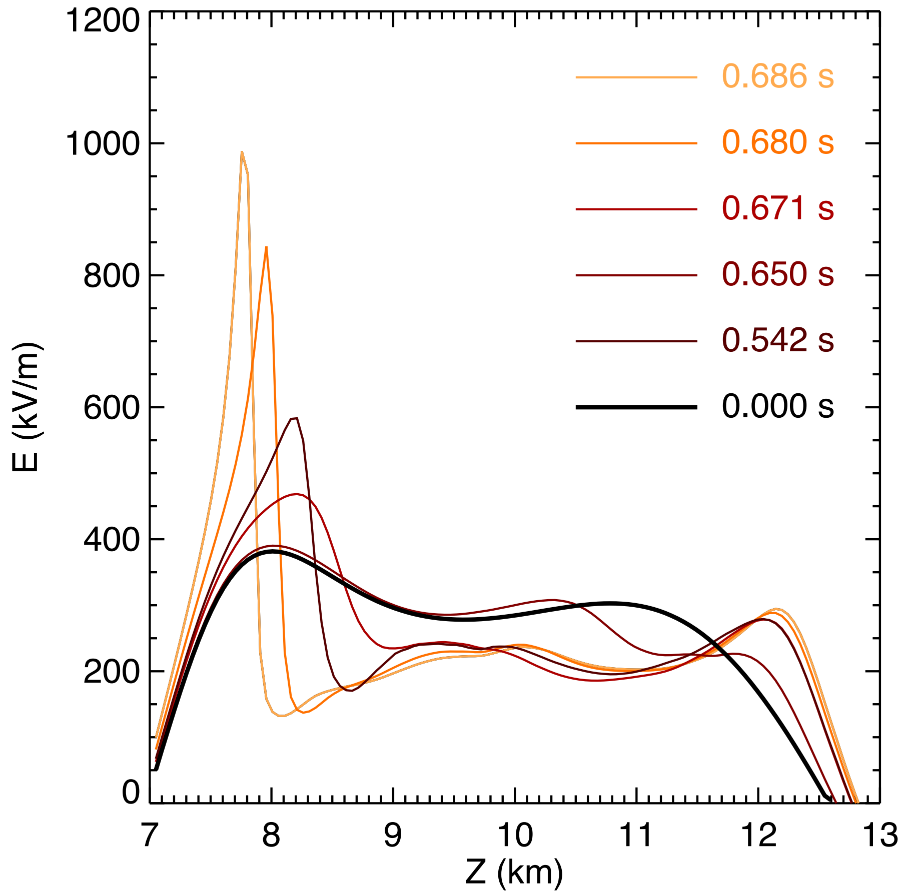
TGFsim: A code that self-consistently models the energetic particles and the electric fields together



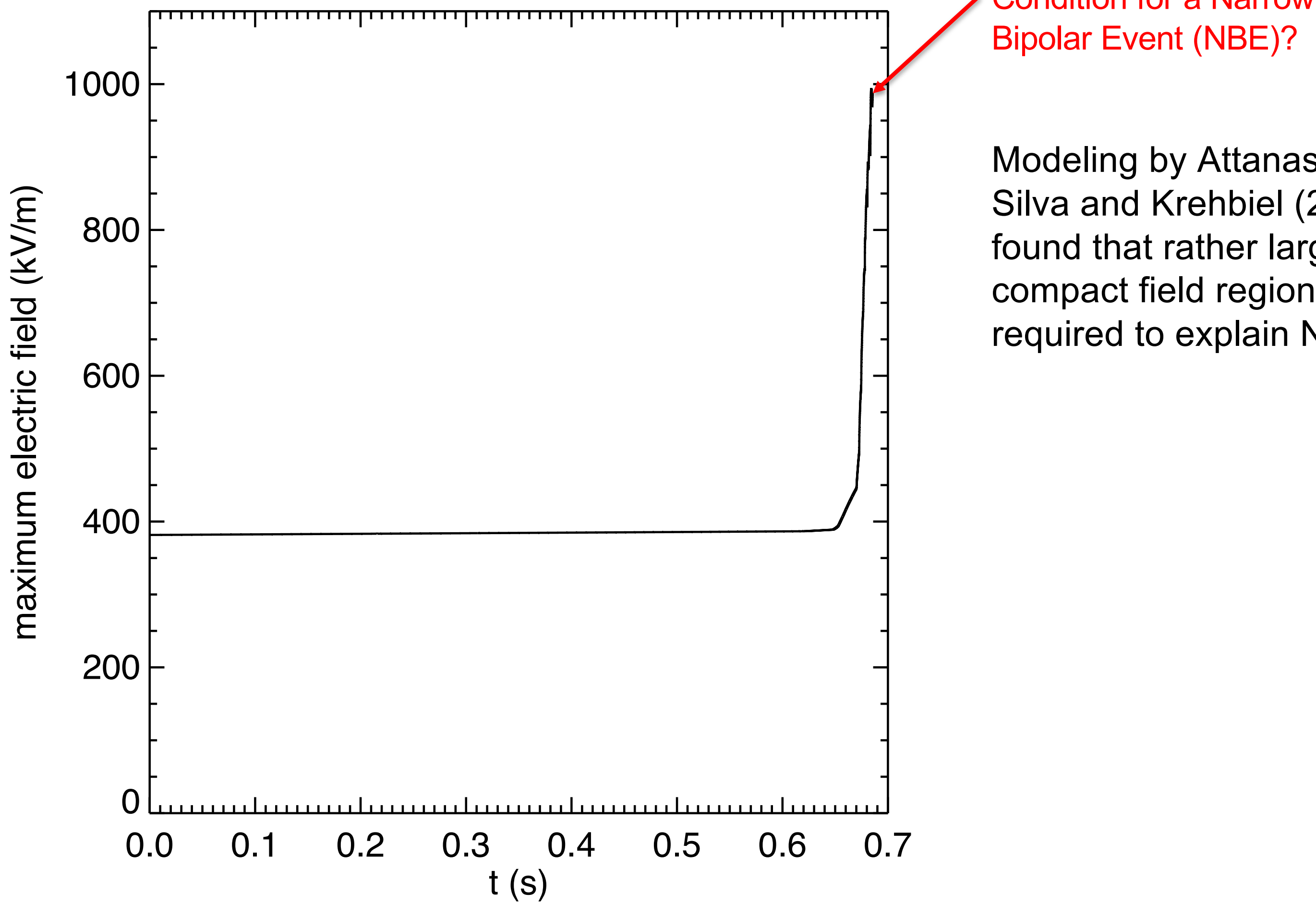
Implementing the TGFsim code



Thunderstorm electric field evolution

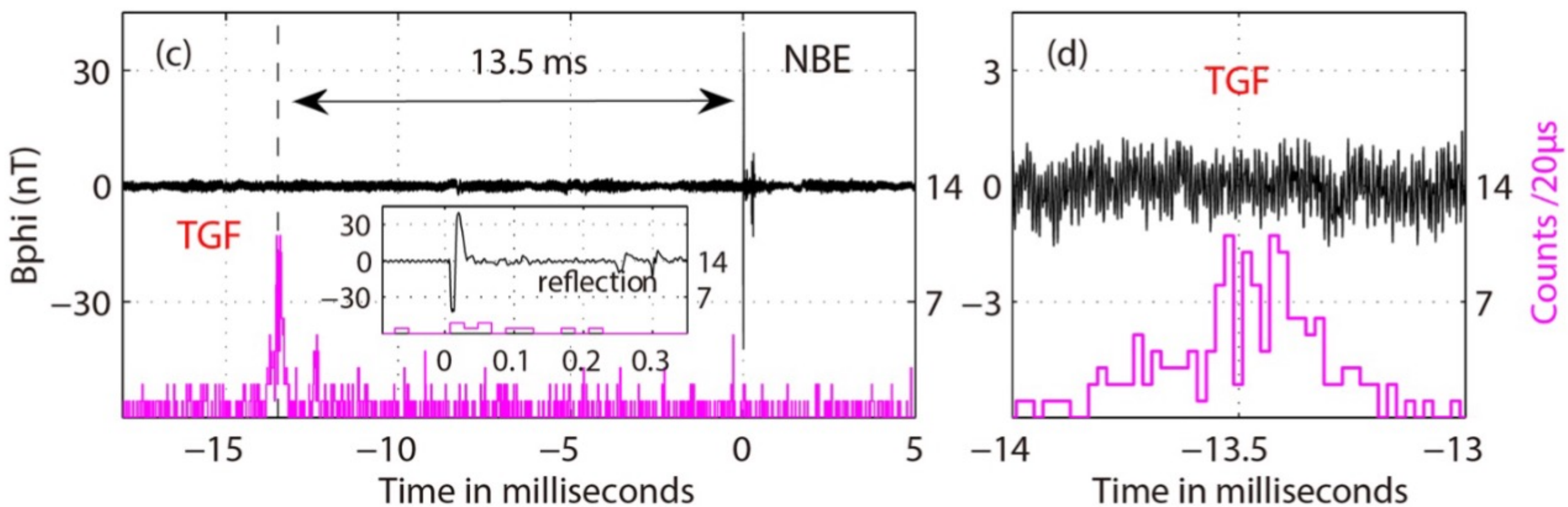


Maximum electric field versus time



Modeling by Attanasio, da Silva and Krehbiel (2021) found that rather large compact field regions are required to explain NBEs

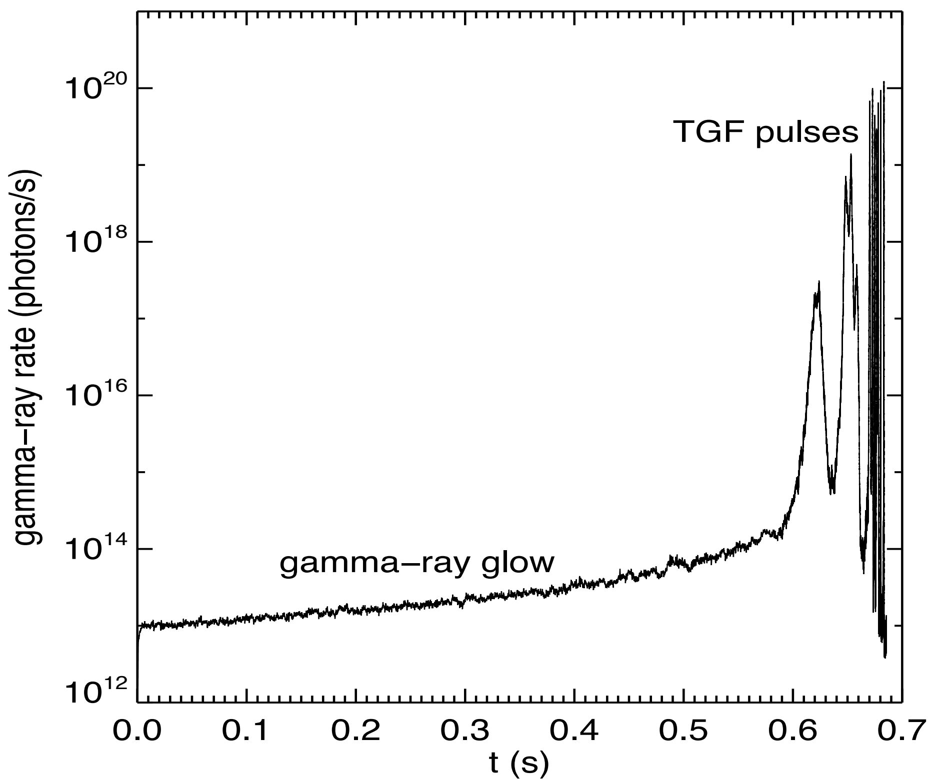
NBEs are observed to follow TGFs



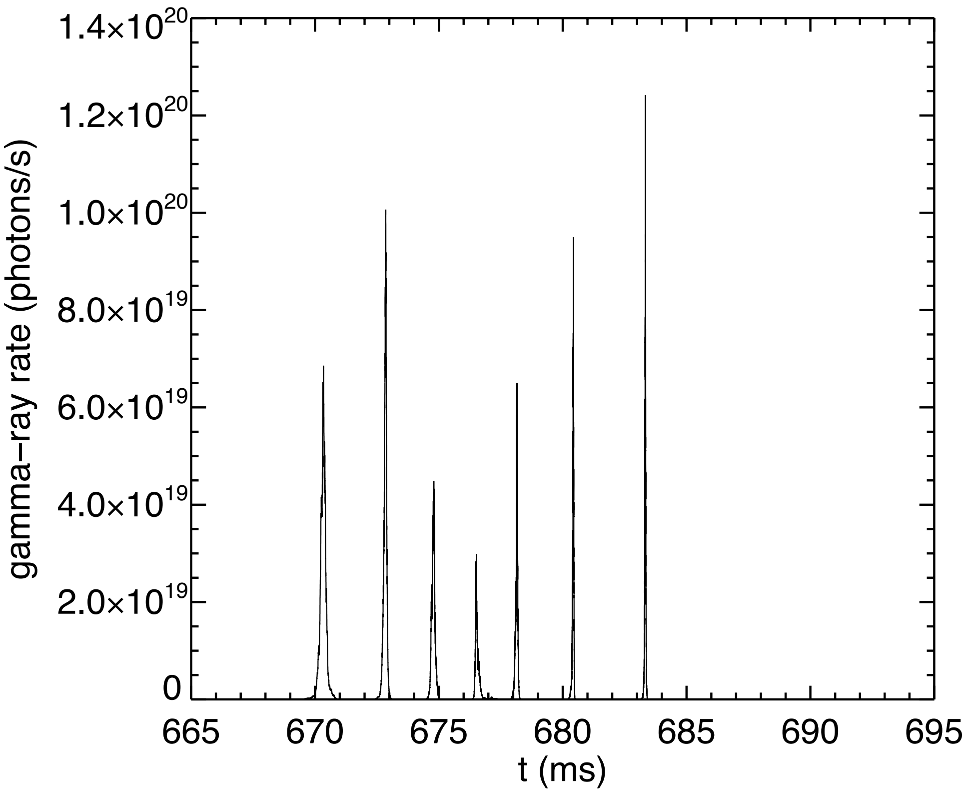
Fermi/GBM TGF followed by a NBE (from Zhang et al. 2021).

Testing the model

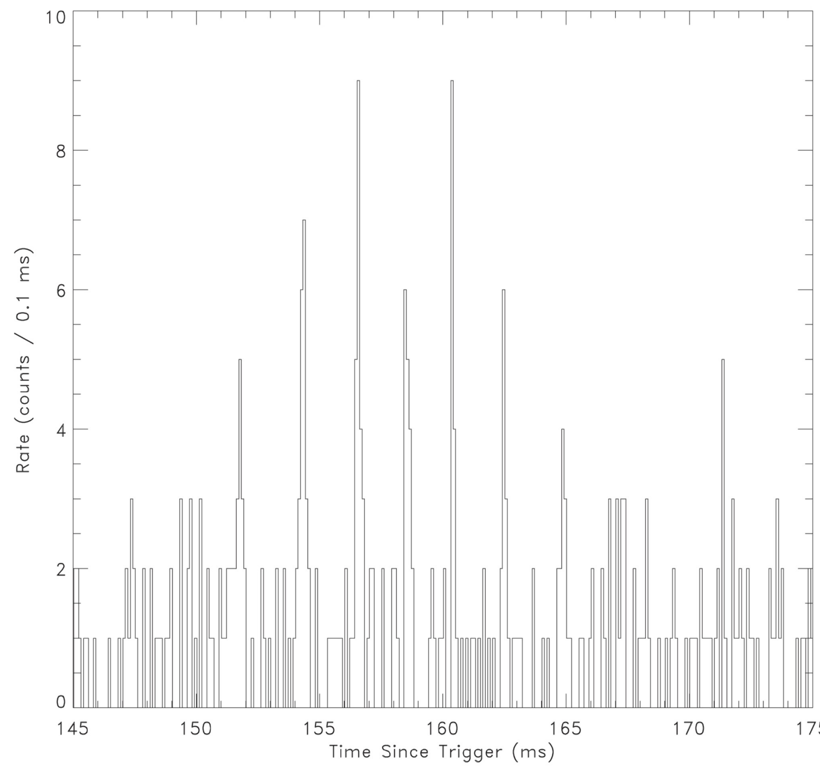
Gamma-ray emissions may be compared with aircraft, balloon, ground-based and space-based observations.



Results of TGFsim model



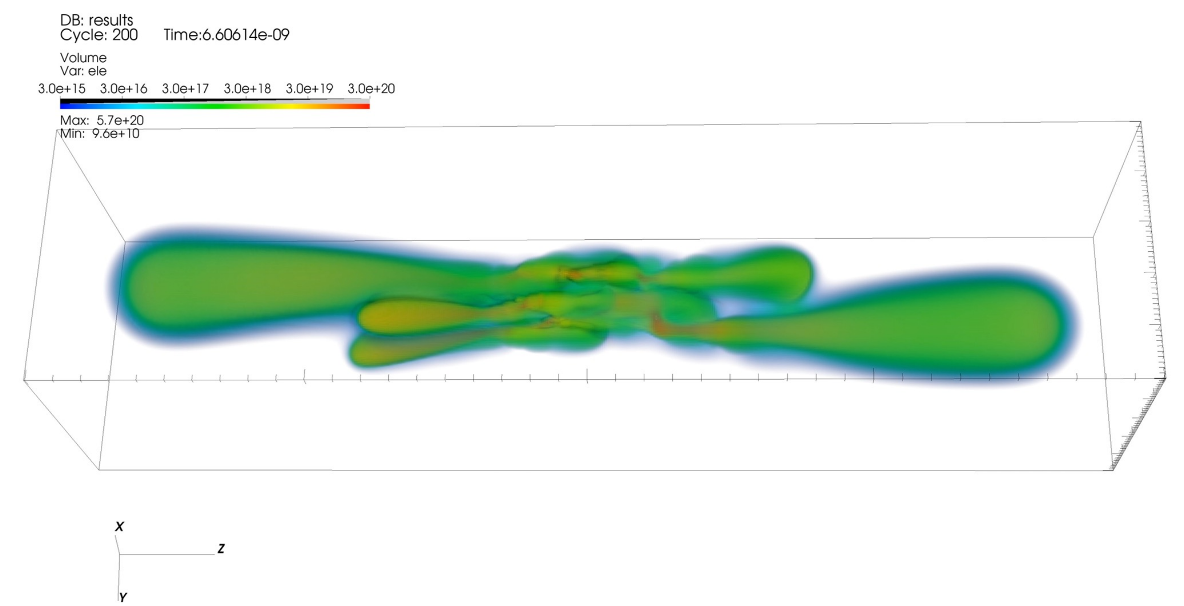
Gamma-ray count rate versus time as measured by CGRO/BATSE for TGF 5578.



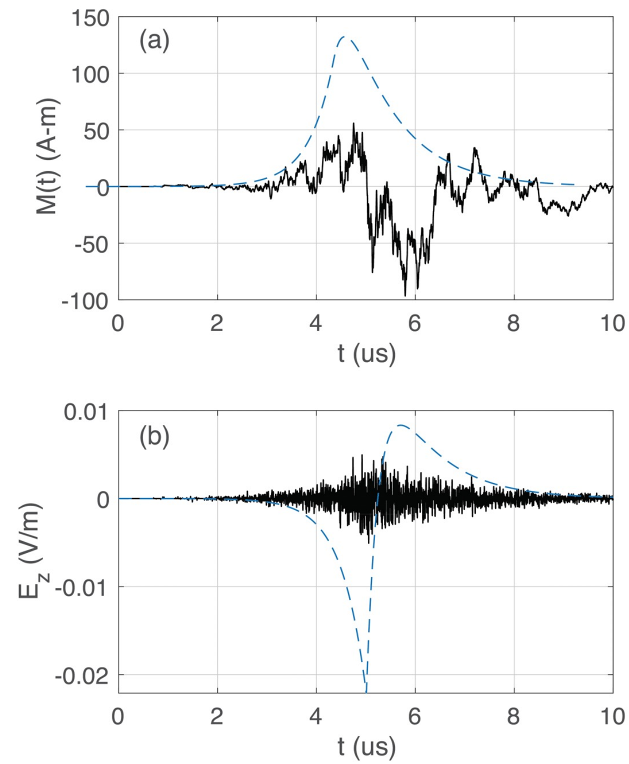
Modeling Streamers and Their Electromagnetic Emissions

The study of streamer discharges and their optical and radio emissions is critical for understanding the physics and observable effects of lightning. It is a challenging task because highly-nonlinear and multiscale processes are involved. Fluid modeling is required to investigate the details of streamer physics, while statistical approaches can provide insights into the properties of large streamer systems.

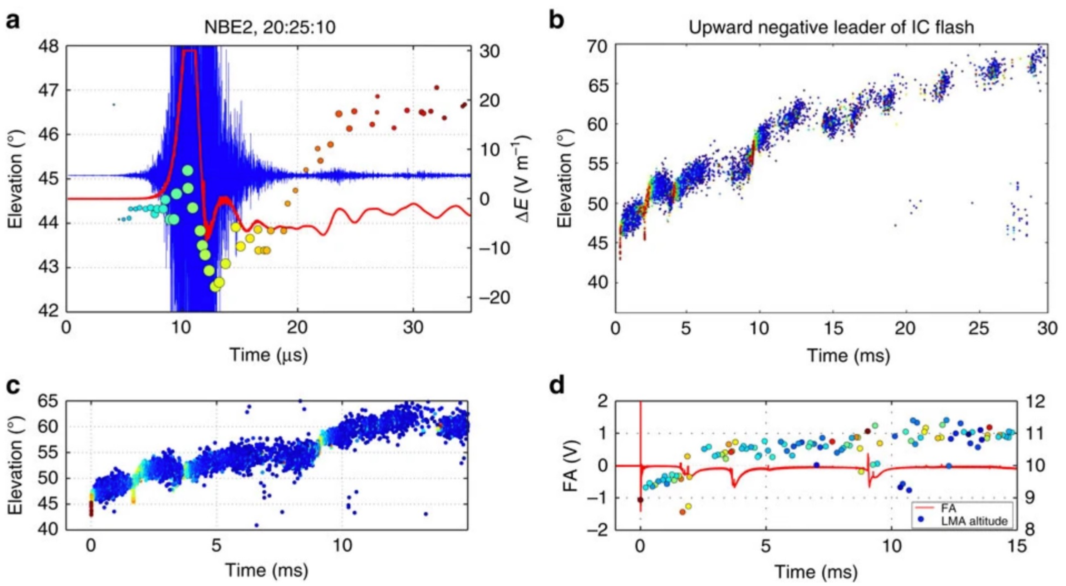
Fully Three-dimensional Fluid Simulation Obtained Using a High-Performance Computer Code Developed by UNH Lightning Group



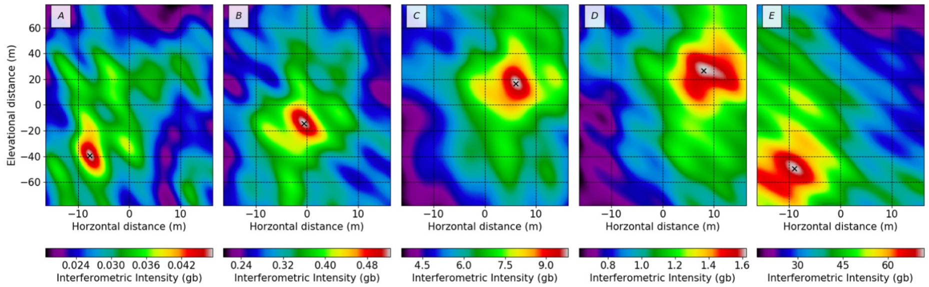
Statistical Modeling Results of Radio Emissions from 10^5 Streamers



Lightning Initiation

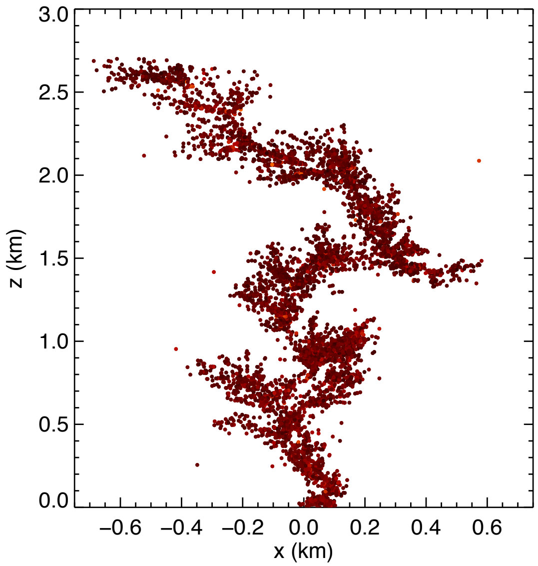


Fast Positive Breakdown: Sferic and VHF source elevations for a Narrow Bipolar Event (NBE) followed by step-leader development. (from Rison et al. 2016)

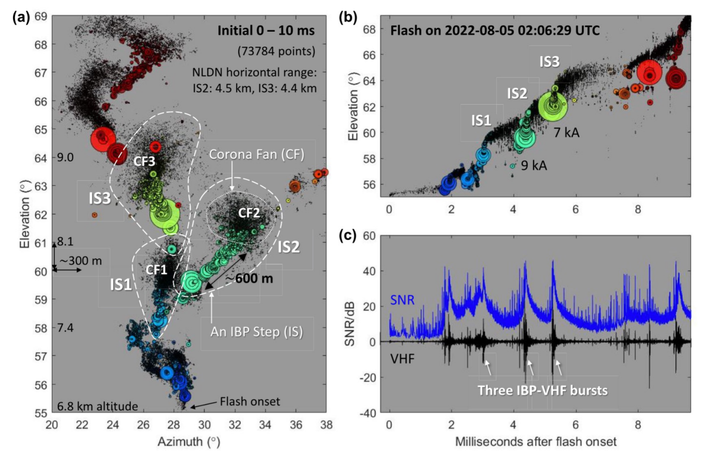


An extremely weak propagating source that initiated lightning, as measured by LOFAR (from Sterpka et al. 2021).

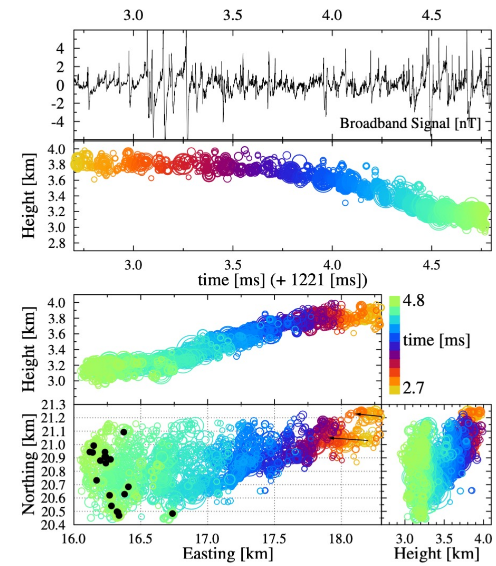
Lightning Propagation



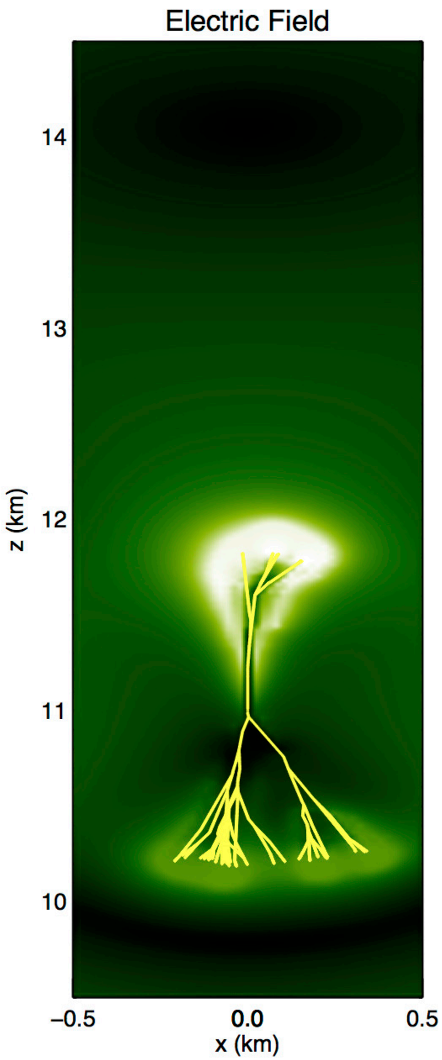
A High-Altitude Negative Leader (HANL) measured by LOFAR (Scholten et al. 2021). Negative leaders above 7 km in altitude look very different from negative leaders at lower altitudes. This HANL is between 9.5 and 10.7 km altitude, moving at approximately a 45-degree angle with respect to vertical.



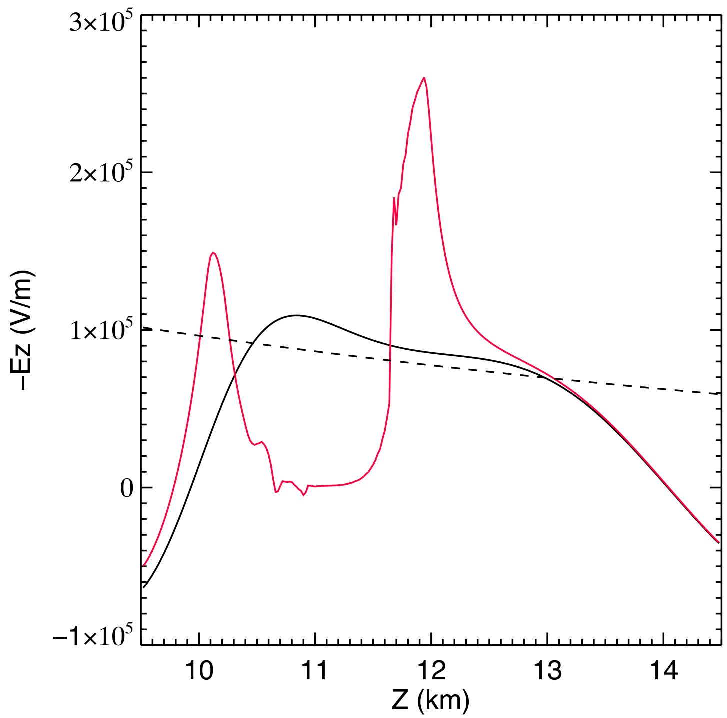
The initial development of an in-cloud lightning flash in 0–10 milliseconds (from Pu and Cummer 2023).



Intensely radiating negative leaders (IRNLs). The black dots label the most recent 0.1 ms strong sources, the arrows the two starting negative leaders. IRNLs emit 100 times more very-high frequency (VHF) and broadband radiation than a more normal negative leader (from Scholten et al. 2022).



Knowing how lightning propagates is also important for modeling TGFs



Physical Approach

- What physics are implemented in this model component?
  - Models were developed to explain high-energy emissions from thunderstorms and lightning
  - Models contain all the necessary physics for describing the high-energy interactions.
  - High-energy components are essential for understanding thunderstorm electric fields.
  - Currently, models are not user friendly, requiring collaboration with experts.

- What are the current gaps?
  - Better electric field and lightning propagation models are needed.
  - Better *in situ* gamma-ray and field measurements are needed.
  - Rapid progress is currently being made by campaigns such a ALOFT.

Model Interoperability

- What are the model inputs?
  - TGFsim model is self-consistent. It only needs background thunderstorm electric fields.

- What are the model outputs?
  - Outputs are the modified electric fields, currents, gamma-rays, RF and optical emissions.
  - Needs to be coupled to more realistic thunderstorm electrification and lightning propagation models

- How will the model components be shared?
  - TBD

Model Use and Validation

- How is this model component validated?

  Compare simulations with other codes, e.g. GEANT4. Such work has already been done. Model results are also fit to gamma-ray, radio and optical observations, with mostly good agreements.
- How will model errors be quantified?

  Generally, codes agree to within 10%, which should be adequate for modeling thunderstorm processes.
- What observations are necessary for validation
  - For high-energy model, compare with aircraft, balloon, space-based and ground-based gamma-ray observation as well as optical and radio observations.
  - ALOFT aircraft data, ground based data from around the world (e.g. UCSC)
  - Better space-based instrumentation would be valuable.
  - ALOFT is a game-changer, Illustrating the value of aircraft observations for studying high-energy processes.

Funding Sources

Sponsoring organization	Funding program	Funding program element	Funding cadence (R = regular interval; I = irregular intervals; L = time-limited opportunity)	Comments
NSF	AGS/PDM & Aeronomy		R	
AFOSR	Space Science		L	

Avenues for Collaborations

- Across national organizations or agencies (public and private)

  YES

- International partnerships

  YES

- What is the balance of student, postdoc, and career-expert work?

  Hopefully, it stays evenly balanced

- Citizen Science

  Maybe citizen science can help with observations, such as energetic particles measurements and optical observations.