Relativistic Runaway Electron Avalanche (RREA) and Terrestrial Gamma Flash (TGF) Research at Stanford University

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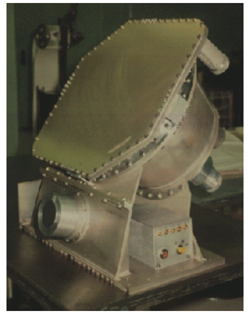
Outline

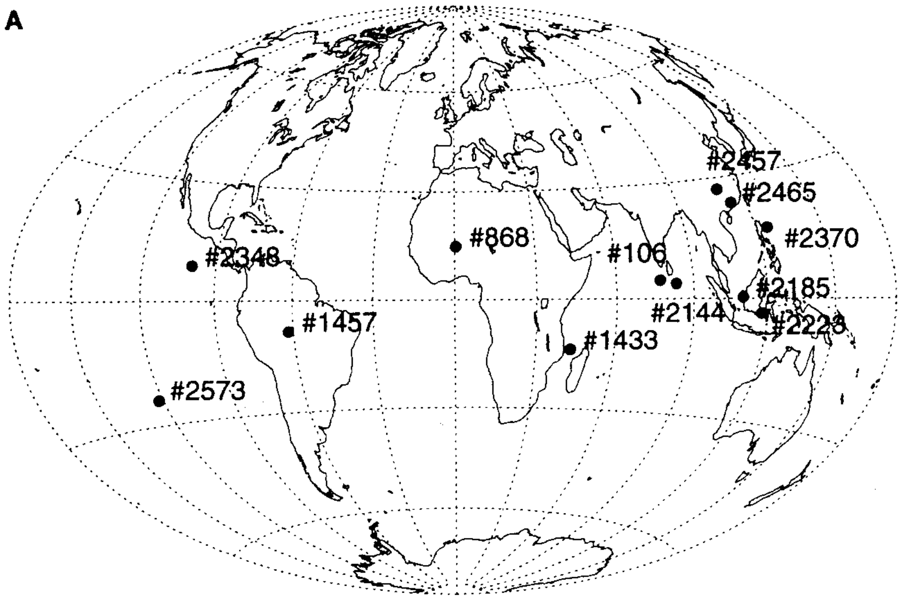
1. Observations
2. Models used
   - Monte Carlo for e^-, e^+, γ (for $\mathcal{E} > 1$ keV)
   - Time-domain fractal lightning (TDFL) model
3. Modelling the mechanisms of RREA production
   - Post-discharge mechanism
   - Lightning EMP
   - Production by lightning leaders
4. Other modelling results
   - Monte Carlo RREA parameters
   - Parameters of the γ source
   - RREA seeding efficiency
   - Terrestrial Electron Flashes (TEF)
   - Neutron flux
5. Conclusions

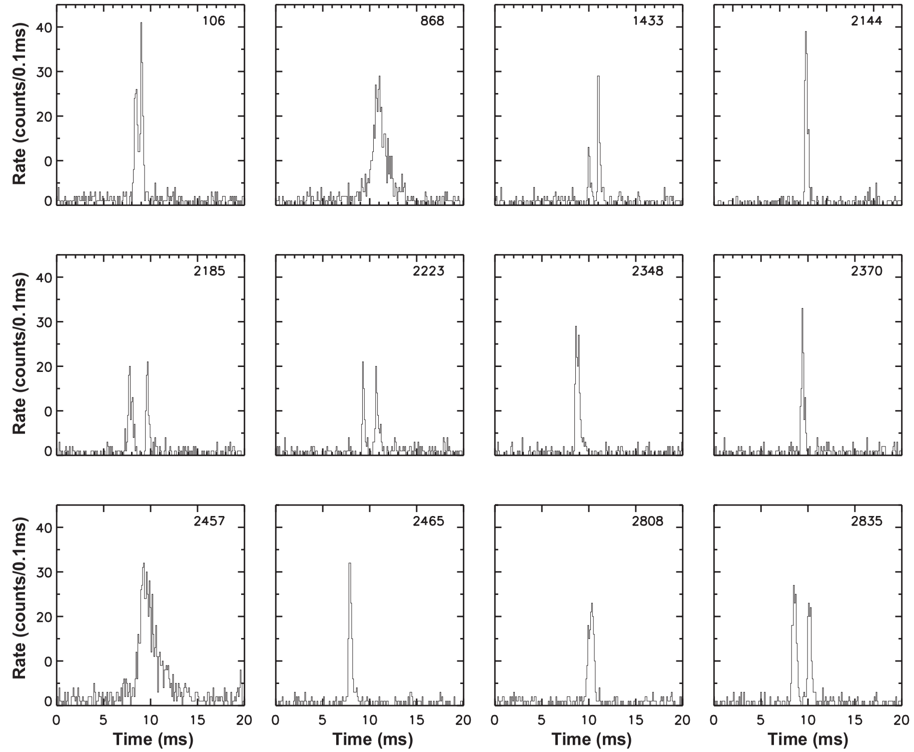
Terrestrial Gamma Flashes (TGF)

- Energetic $>$40 MeV
- Short $<$1 ms
- Believed to be created by runaway relativistic electron avalanches (RREA)
- Observed by low Earth orbiting satellites

BATSE/CGRO





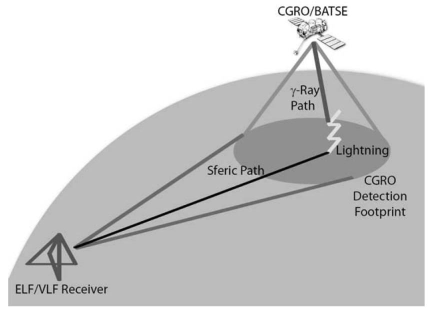


Later observations: RHESSI, FERMI, AGILE

VLF observations of TGF-associated sferics

[*Cohen et al*, 2006]

VLF observations of lightning signals (sferics) have shown the TGF occur in association with thunderstorms, or even with individual lightning discharges.



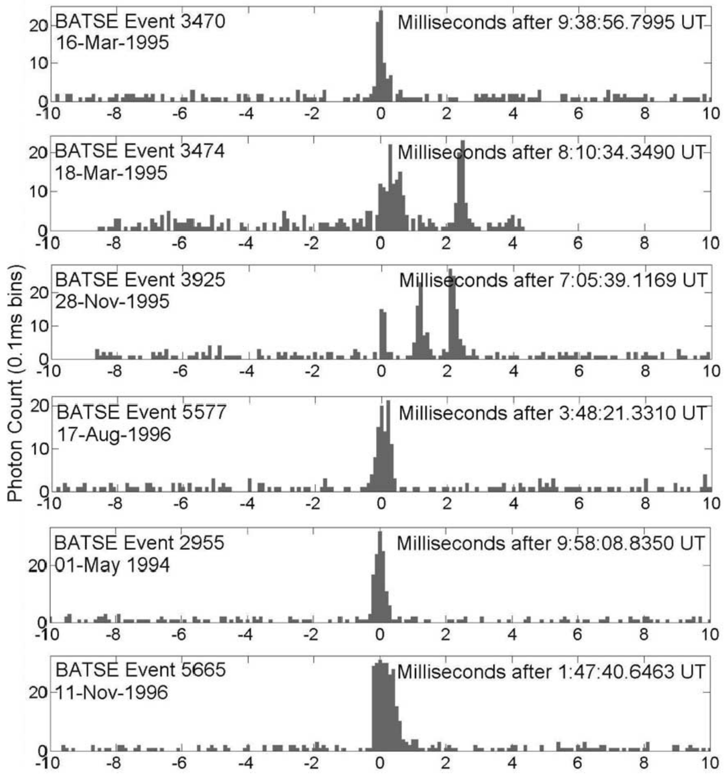


Figure 4. BATSE waveforms corresponding to the six TGF cases analyzed.

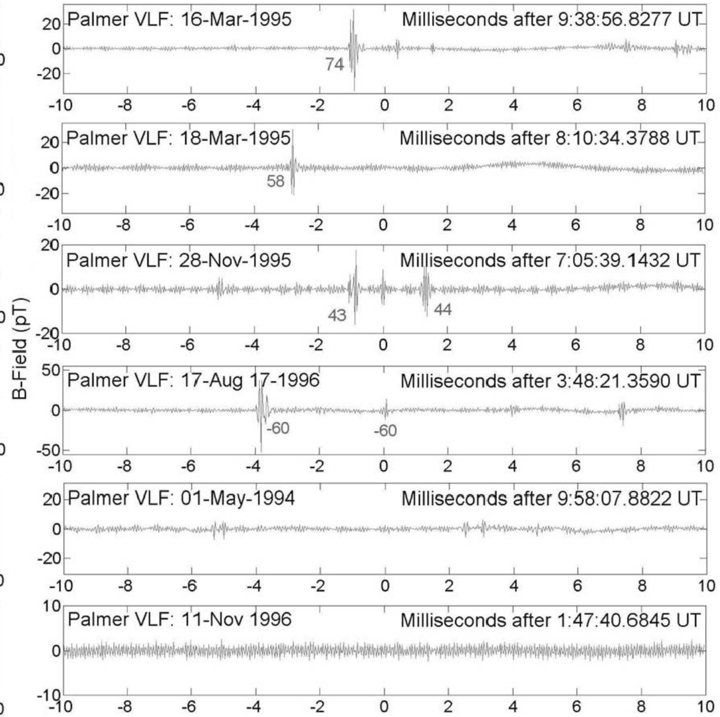


Figure 5. ELF/VLF waveforms corresponding to the six TGF cases analyzed.

VLF observations of TGF-associated sferics

[*Cohen et al*, 2010]

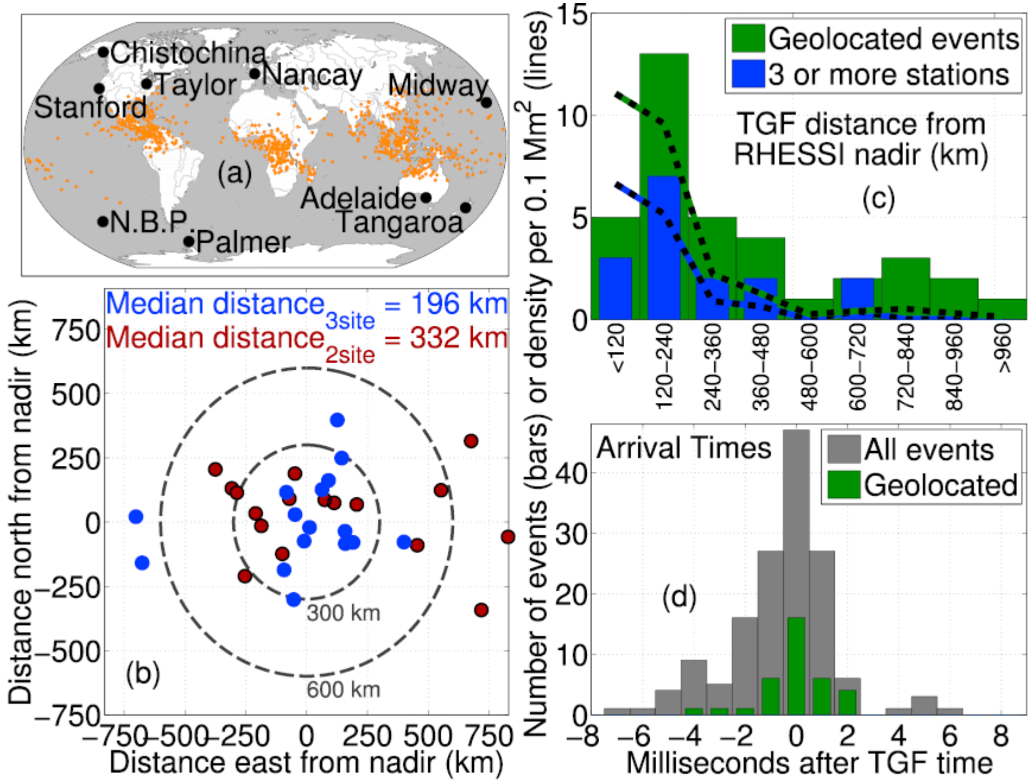


Figure 1. (a) VLF receivers used (black), and locations of all RHESSI-observed TGFs (orange), (b) scatterplot of TGF source locations with respect to RHESSI nadir, separately for 2-site cases (red) and >=3-site cases (blue), (c) distribution of distances from RHESSI nadir to TGF source, (d) distribution of arrival times of VLF sferic with respect to TGF time.

Overview of mechanisms of TGF production

The electric fields which accelerate the runaway electrons may be caused by several mechanisms:

1. quasi-electrostatic fields produced after lightning discharges;
2. the electromagnetic pulses radiated by rapid lightning return strokes;
3. the direct production of radiation by the lightning channel.

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Monte Carlo for e^-, e^+, γ

Description:

- Relativistic motion $\frac{d\mathbf{p}}{dt} = -e\mathbf{E} - \frac{e}{m\gamma}\mathbf{p} \times \mathbf{B} + \mathbf{G}(t)$
- $\mathbf{G}(t)$ – random elastic scattering and inelastic energy losses (excluding losses from new e^- creation)
- New e^- from ionization

Results:

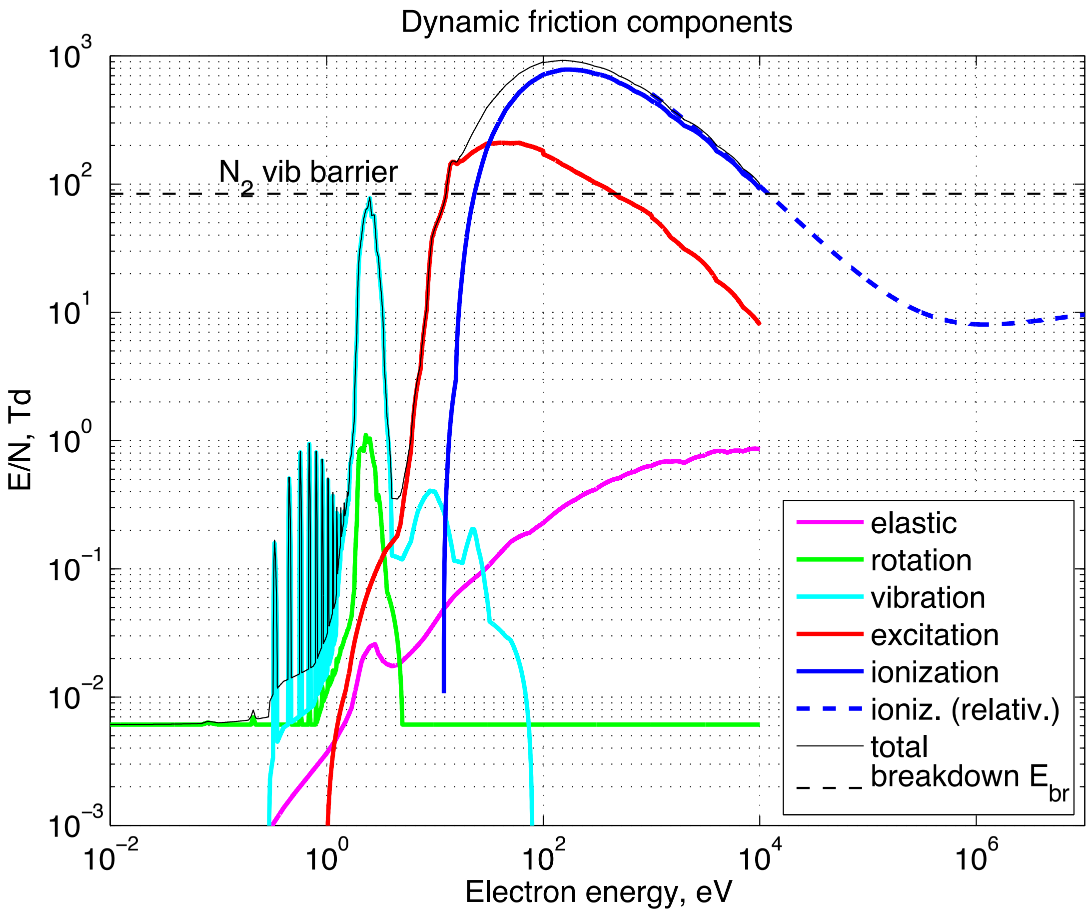
- Electron distribution
- Drift velocity
- Electron number density evolution

Applications:

- Relativistic electron avalanche in $\mathbf{E}$
- Energetic e^- precipitation
- γ penetration into atmosphere
- Propagation of γ from terrestrial gamma flashes (TGF)

Dynamic friction force

(effective force on electrons moving through air)



$$F = \sum N_k \sigma_k(v) \Delta\mathcal{E}_k$$

$$\frac{E}{N} = \sum \frac{N_k}{N} \sigma_k(v) \frac{\Delta\mathcal{E}_k}{e}$$

Inelastic processes:

1. Rotational
2. Vibrational
3. Electronic level excitations
4. Dissociative losses
5. Ionization

Relativistic runaway threshold $E_t/N_m \approx 8$ Td at ~1 MeV

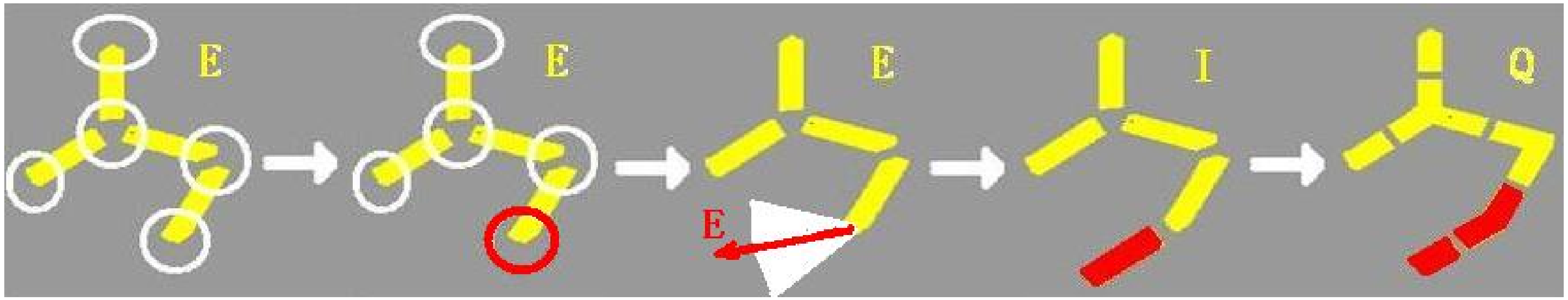
1 Td$= 10^{-21}$ V m^2

Outline

Description of TDFL

- Geometry Segmentation (I — current, Q — charge elements)

- Channel Branching, with space leader implementation



Q, I, **E** update

- Electric Field Integral Equation (EFIE):

$$\mathbf{E}(\mathbf{x},t) = \frac{1}{4\pi\varepsilon_0}\int d^3\mathbf{x}' \left\{ \frac{\hat{\mathbf{R}}}{R}\left[\rho(\mathbf{x}',t')\right]_{\rm ret} + \frac{\hat{\mathbf{R}}}{cR}\left[\frac{\partial\rho(\mathbf{x}',t')}{\partial t'}\right]_{\rm ret} - \frac{1}{c^2R}\left[\frac{\partial\mathbf{J}(\mathbf{x}',t')}{\partial t'}\right]_{\rm ret}\right\}$$

- Charge conservation, Ohm's law

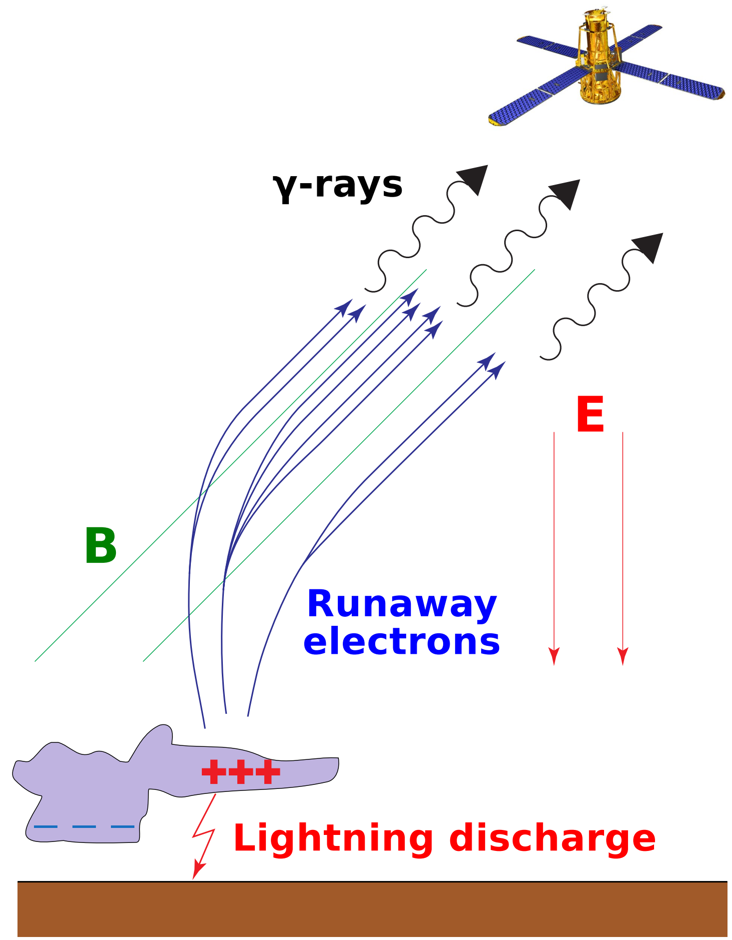
- Thin wire approximation
- Method of moments/Boundary element method
- Repeat, marching on in time

Outline

Outline

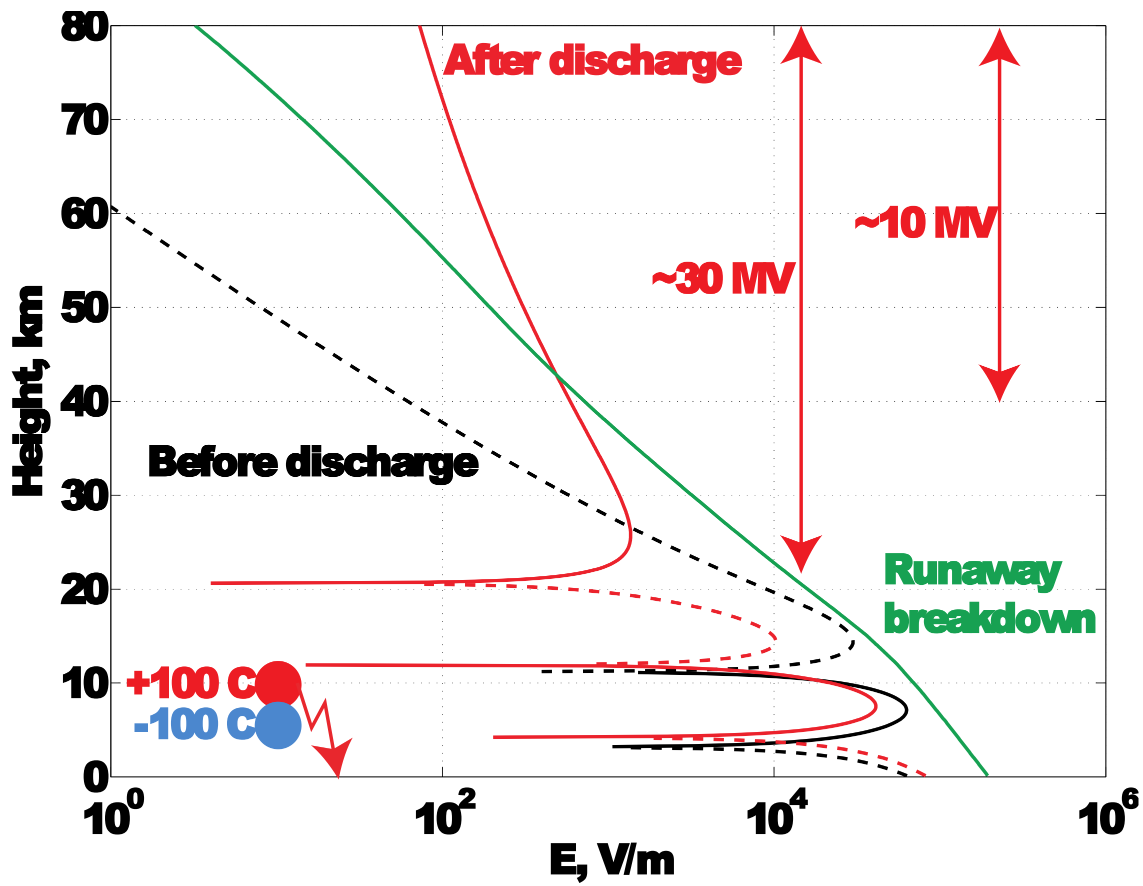
Quasi-electrostatic fields produced after lightning discharges

- Electrons are accelerated by *E* field following a $+$CG discharge
- Number of electrons is increased due to ionization
- Gamma rays are produces by bremsstrahlung from energetic electrons ($>$35 MeV energy)
- Emission is forward-directed
- Direction of electron motion is determined by elastic collision rate and **B**.



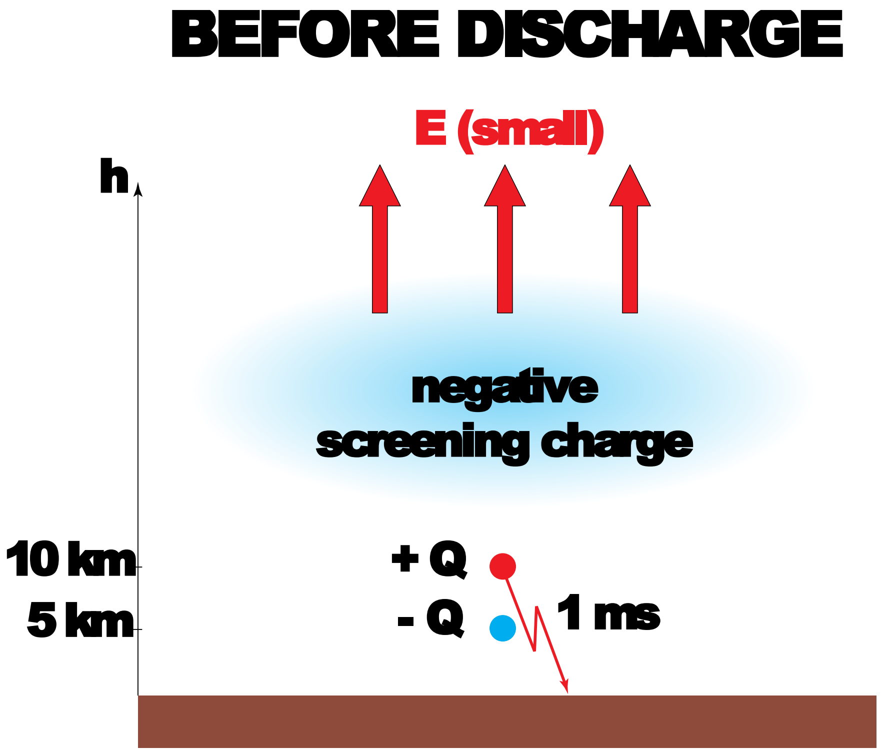
Post-discharge electric field

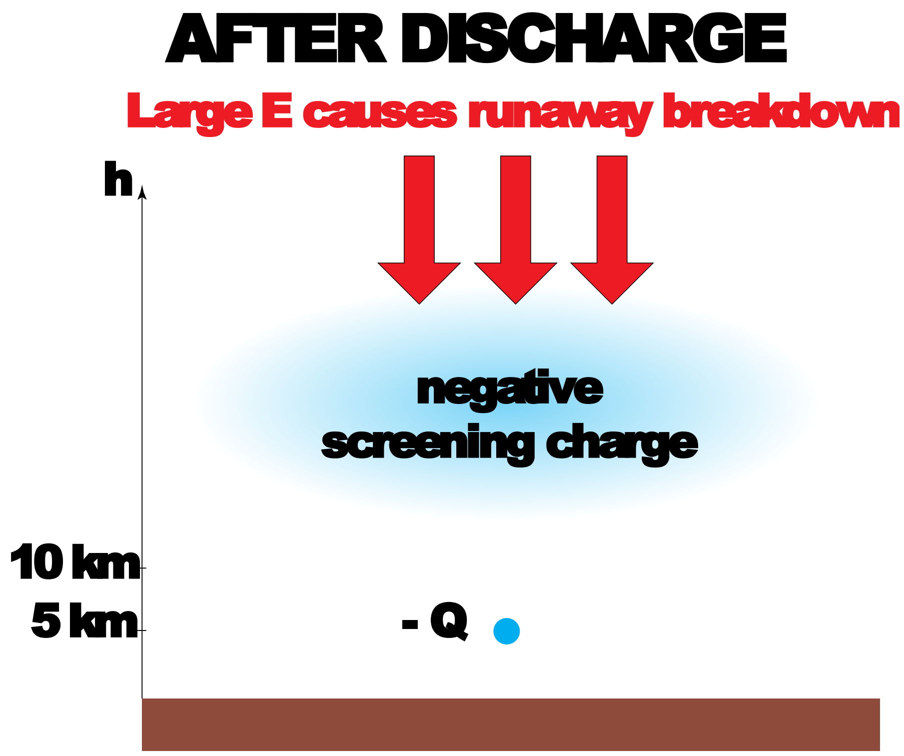
- Exceeds relativistic runaway threshold
- Accelerates electrons upward
- In atmosphere with exponential conductivity profile



$$\Phi_{\rm disch} = \frac{Q}{4\pi\varepsilon_0 r}\left(e^{-(r+z)/2H} - 1\right)$$

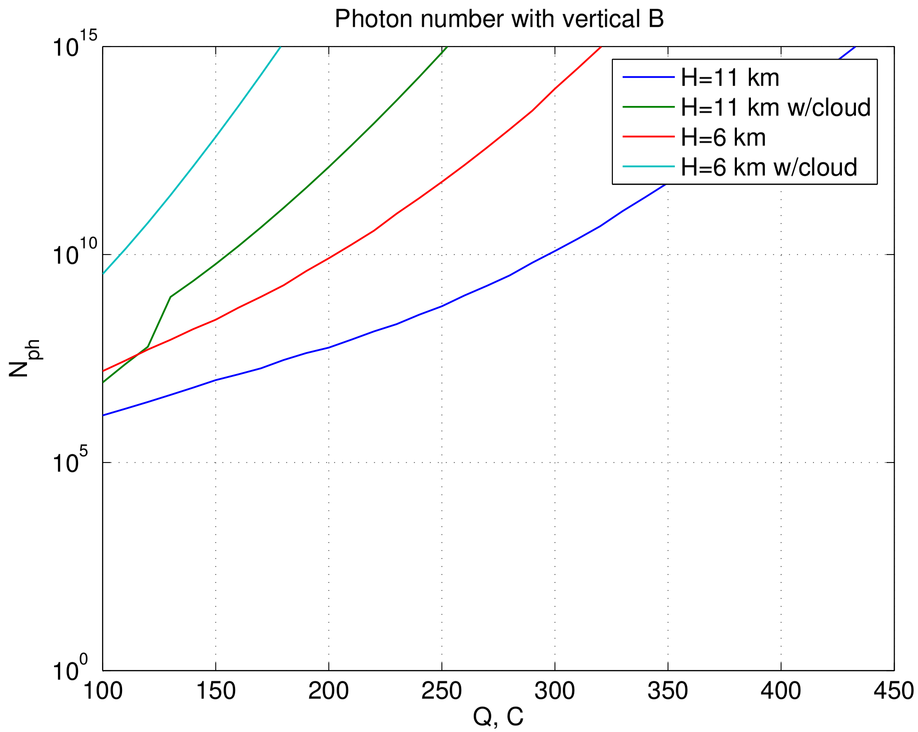
Quasi-electrostatic field

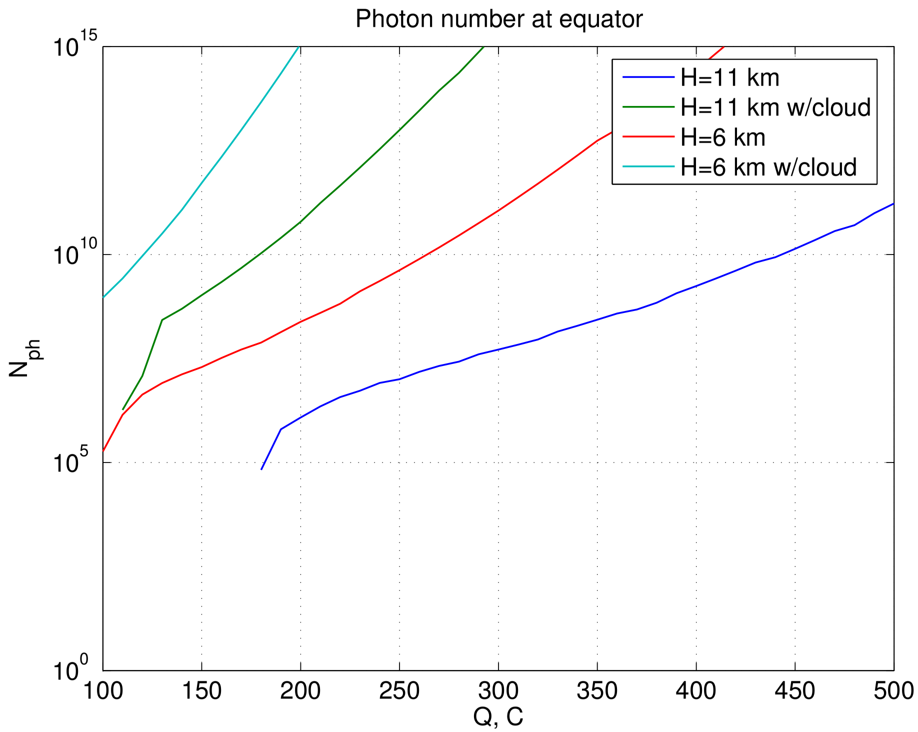




Typical Q to match observed γ number of 3×10^{15}

Two different ionosphere conductivity profiles, vertical and horizontal **B**.



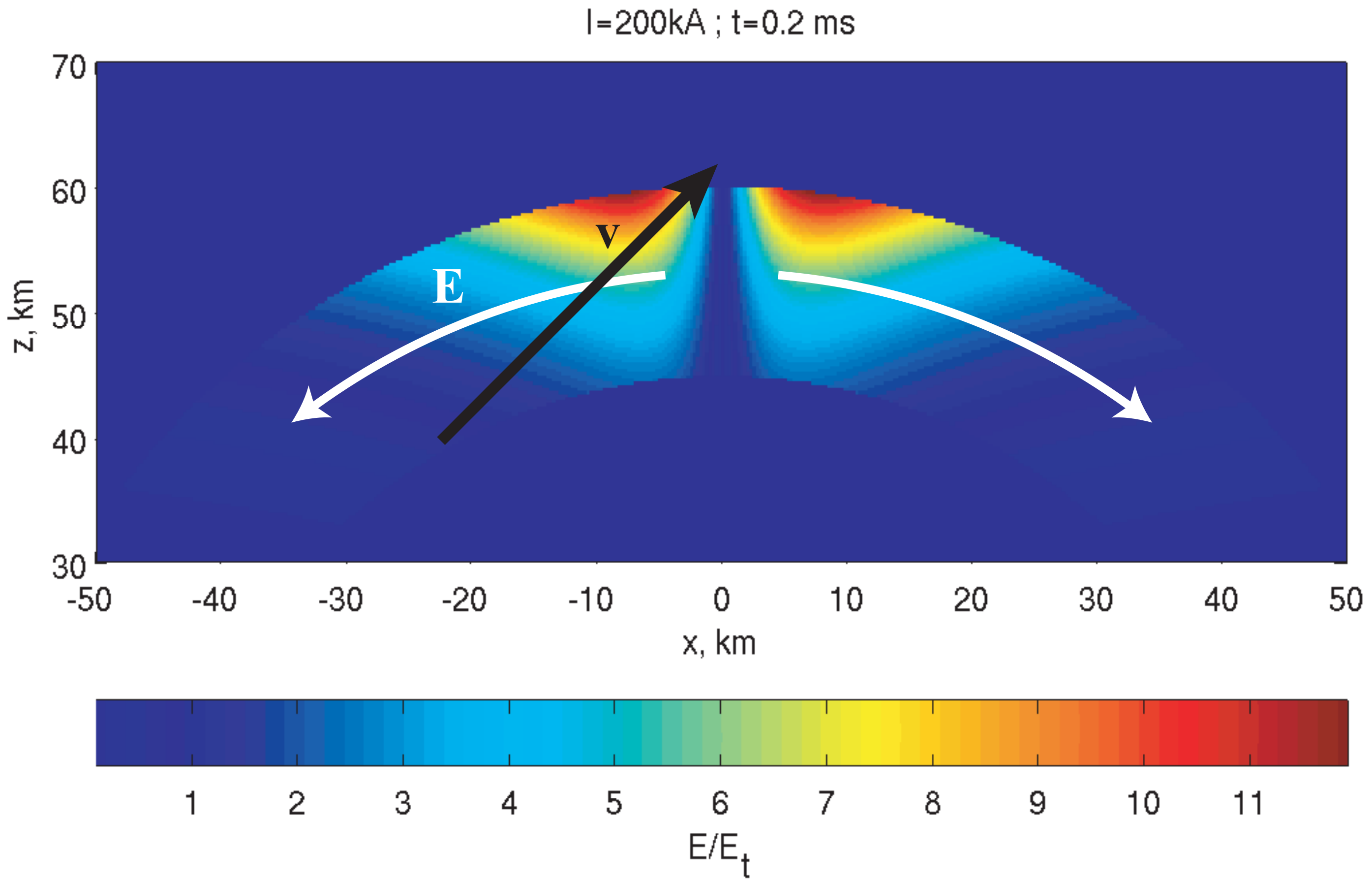


Post-discharge QES mechanism requires a very large charge to be removed

Outline

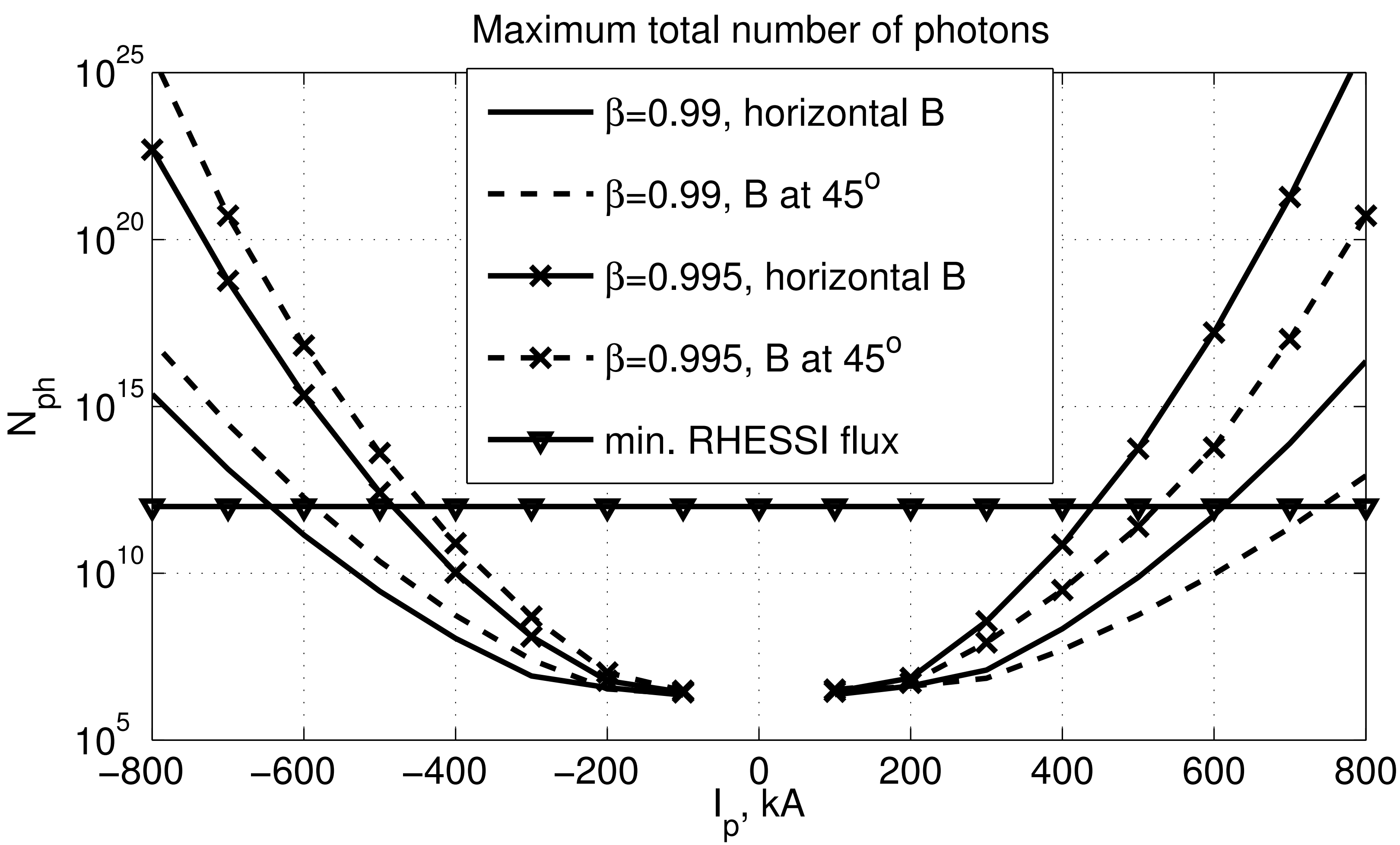
EMP radiated by rapid lightning return strokes

$$E(t) = \frac{\mu_0 I(t - R/c)}{2\pi R} \frac{c\beta \sin\theta}{1 - \beta^2 \cos^2\theta}$$



TGF production

The optimal angle gives partial synchronization



EMP vs QES model

Return-stroke EMP [*Inan and Lehtinen***, 2005]**

- Can produce TGF at the geomagnetic equator
- Runaway electrons do not escape

Quasi-electrostatic (QES) [*Lehtinen et al***, 1999]**

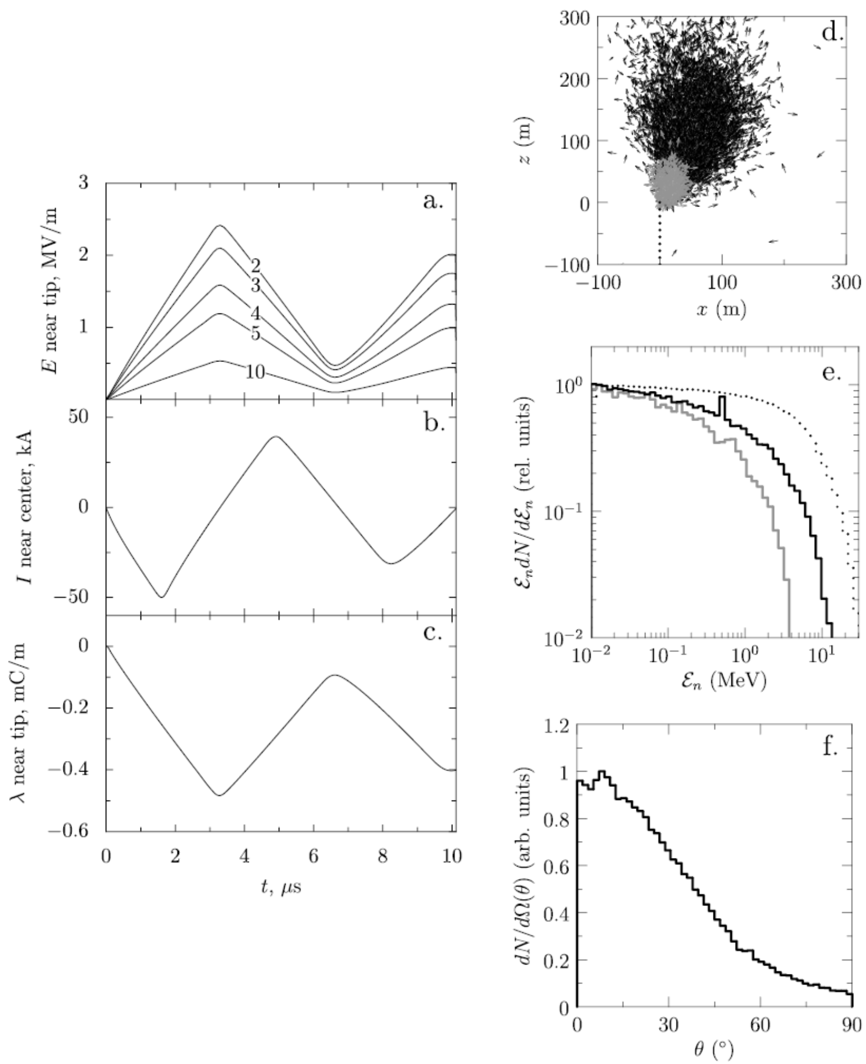
- Cannot produce TGF at the geomagnetic equator
- Runaway electrons are predicted to escape to ionosphere

Extreme parameters of lightning discharges are required for both mechanisms to produce the observed levels of TGF emissions.

Outline

Direct production of radiation by the lightning channel

[*Carlson et al.*, 2010]



(left) Electric field is intensified at the leader tip ($h = 10$ km, $I = 50$ kA, $E = 37$ kV/m, $E/E_t = 0.5$), at $r = 2$, 3, 4, 5, and 10 m. (right) Produced γ distribution, at 1 and 3 ms.

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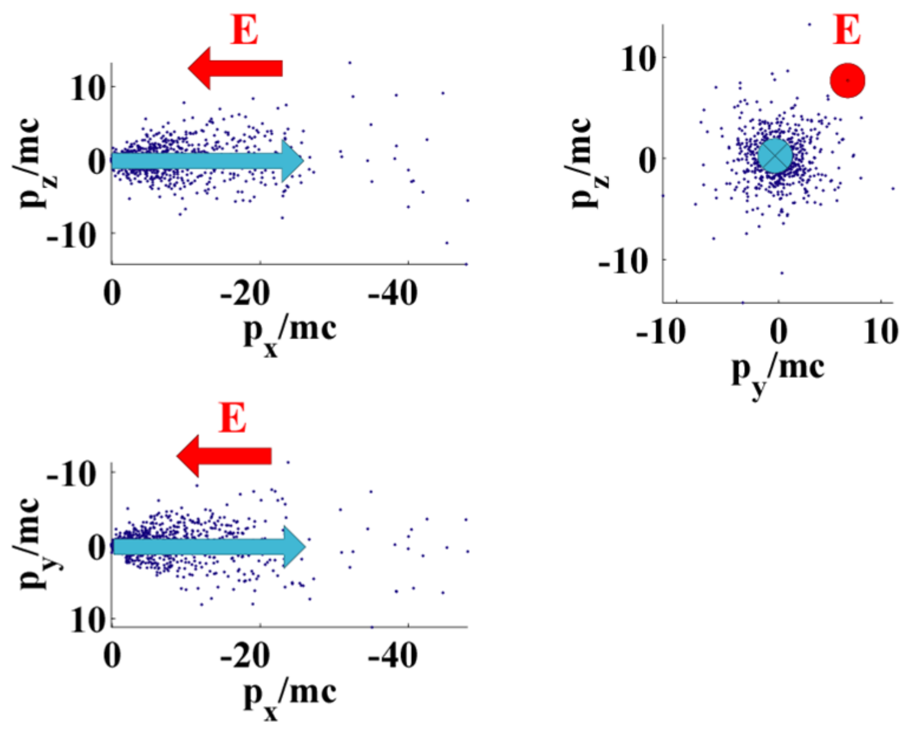
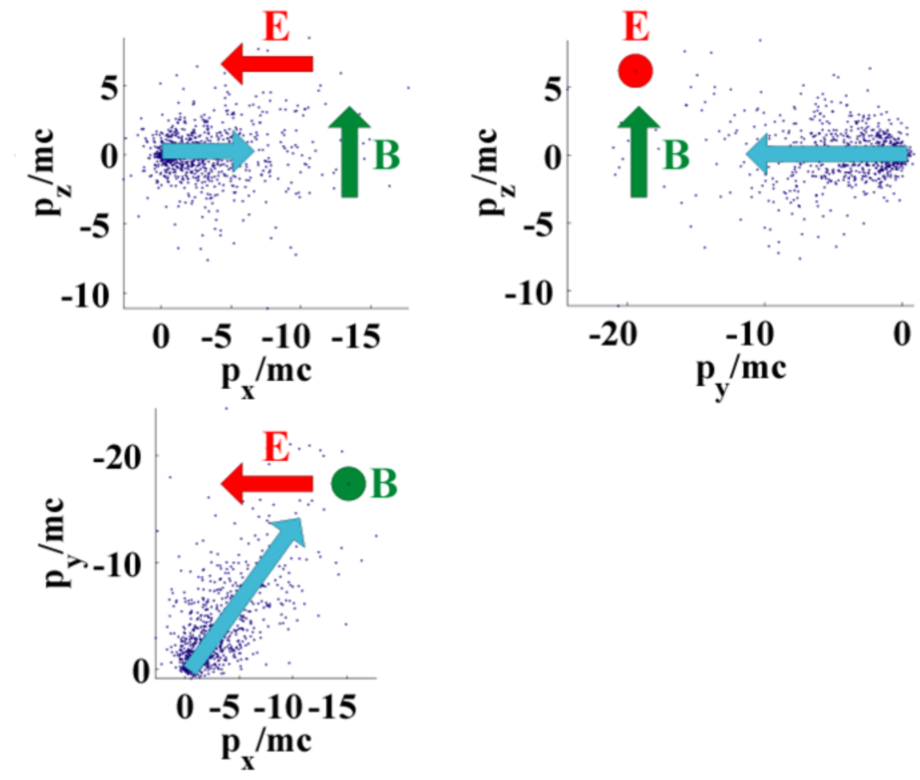
Energetic e^- distribution from Monte Carlo

$E/E_t = 5,\ B = 0$	$E/E_t = 5,\ B = cE,\ \mathbf{B} \perp \mathbf{E}$

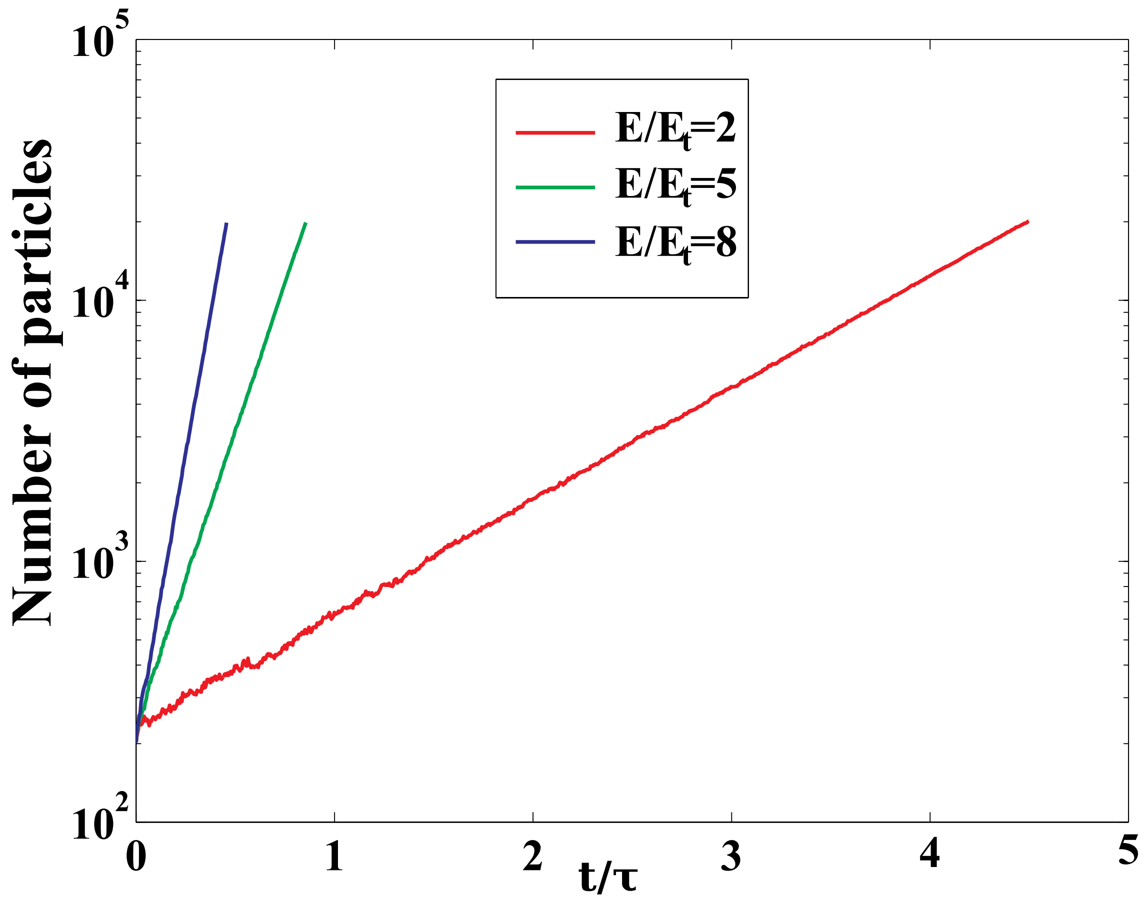




RREA growth rate

$N(t) = N_0 e^{Rt}$

- $R \approx [(\delta - 1) + 0.04(\delta - 1)^2]/\tau$,
  $\tau = (2\pi N_m Z_m r_0^2 c)^{-1}$
  r_0 class. e^- radius
  Z_m molecular charge
  $\delta = E/E_t$ overvoltage
- R decreases slowly with increasing $B_\perp$
- Quenched when $B_\perp > 2E/c$



Outline

Constraints from satellite observations

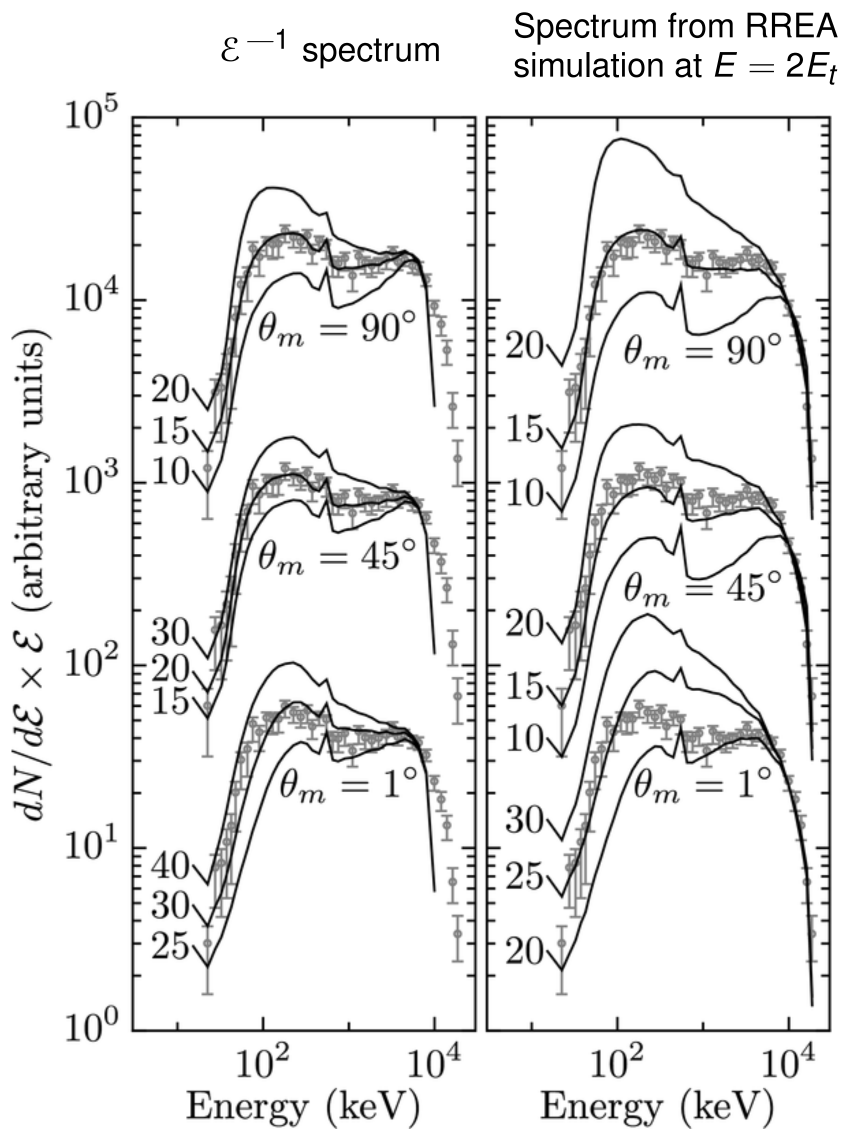
[*Carlson et al*, 2007]

Goal Infer parameters of the gamma source (energy, altitude, shape/direction of initial beam, ...) without knowing the exact mechanism of production

Method Use a Monte Carlo model to propagate gamma photons from atmosphere to the satellite

Given Observed spectrum and flux of gamma rays at a satellite (BATSE, RHESSI)

Comparison with RHESSI spectra



- Gray bars - RHESSI spectrum
- Solid lines are calculated spectra for different altitudes (given in km)
- θ_m is the opening angle of the beamed source

Best fit:

- $\theta_m \geqslant 45°$
- $h = 15$–20 km
- Spectrum from RREA

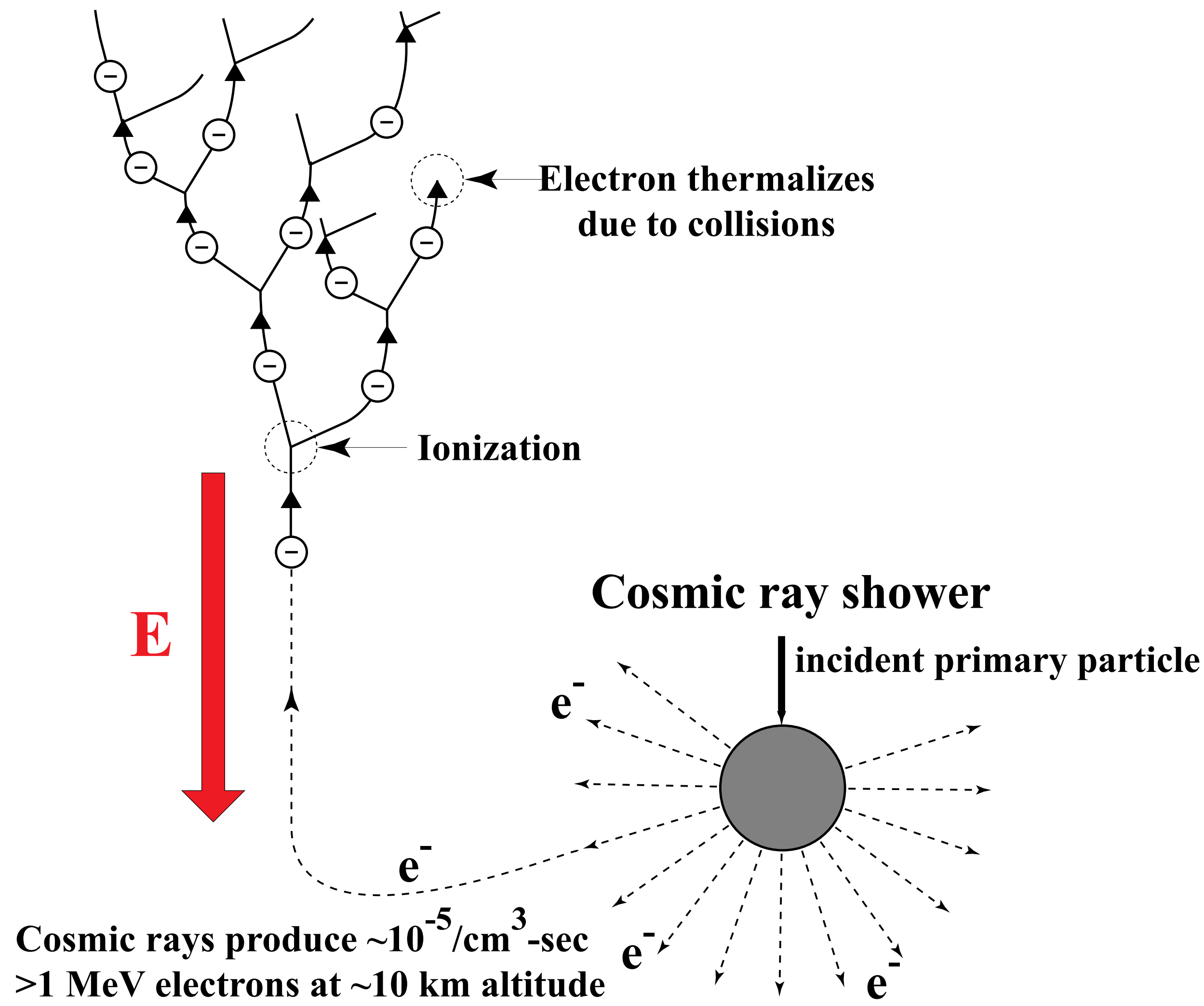
Consistent with *Dwyer and Smith* [2005]

Outline

RREA are seeded by cosmic rays

RREA may be seeded by an energetic cosmic ray particle:

- electron
- positron
- photon
- muon



RREA seeding efficiency by various particles

[*Carlson et al*, 2008]

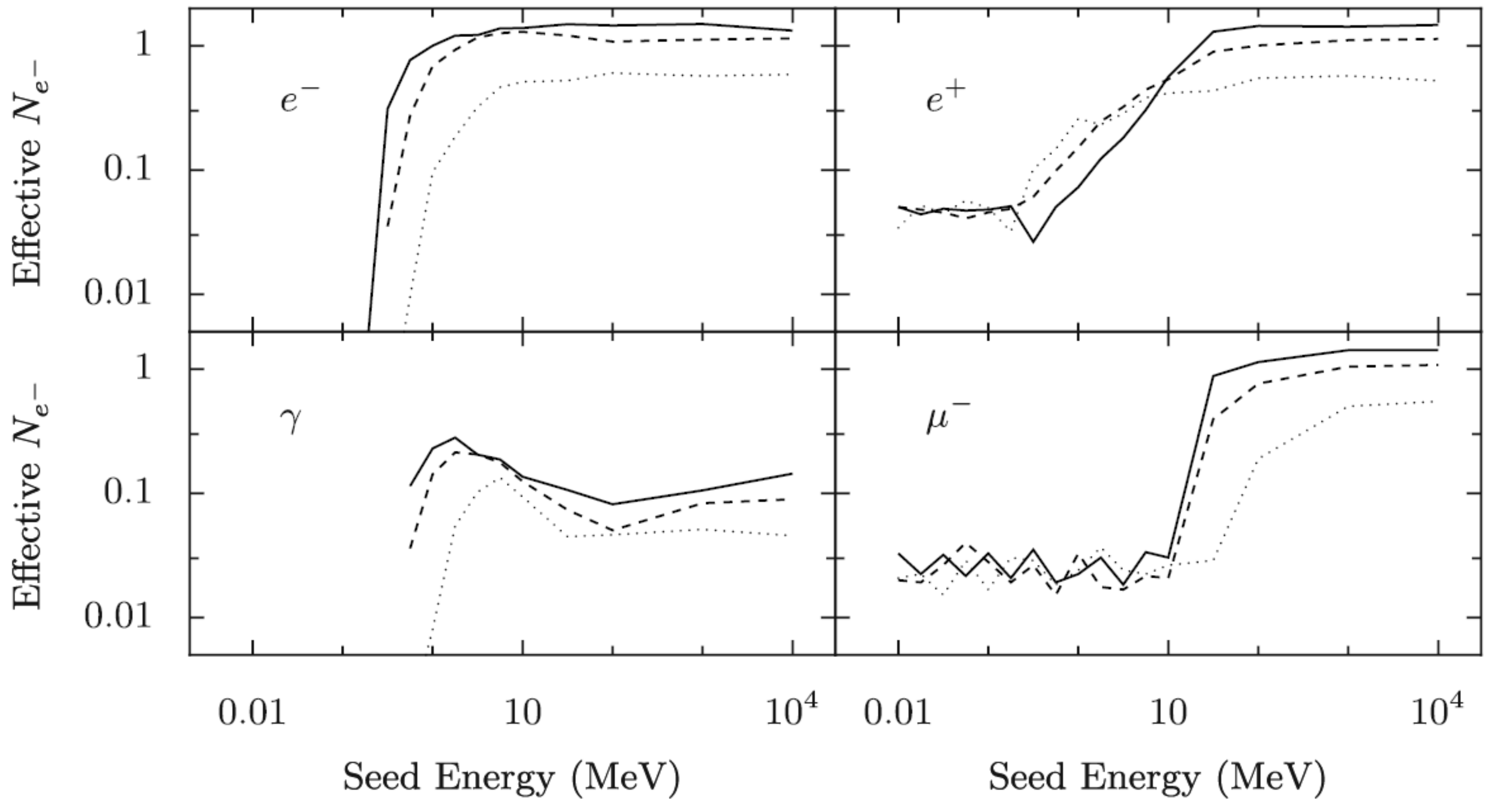
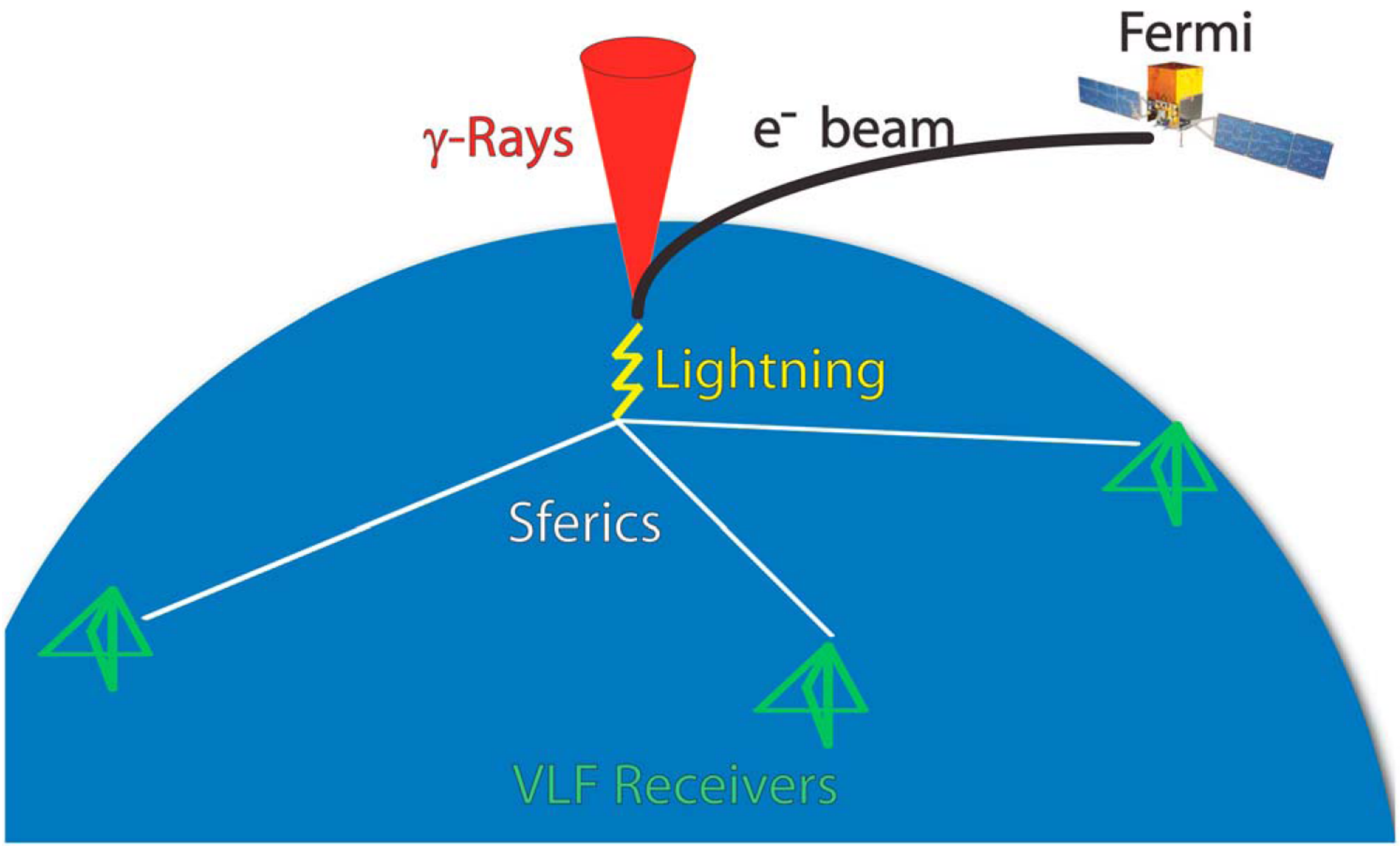


Figure 3. Effective number of downstream 1 MeV seed electrons versus initial particle energy for various seed particle types, energies, and directions. Seed particle momentum in direction of avalanche growth (downstream) shown in solid lines, perpendicular (cross-stream) shown in dashed lines, and opposite (upstream) shown in dotted lines.

Outline

Terrestrial Electron Flashes (TEF)

It was shown that the electrons produced in Compton scattering process of gamma photons may reach ionosphere and be observed by satellites in the form of Terrestrial Electron Flashes (TEF).



TEF simulations and observations

Simulations [*Carlson et al*, 2009]

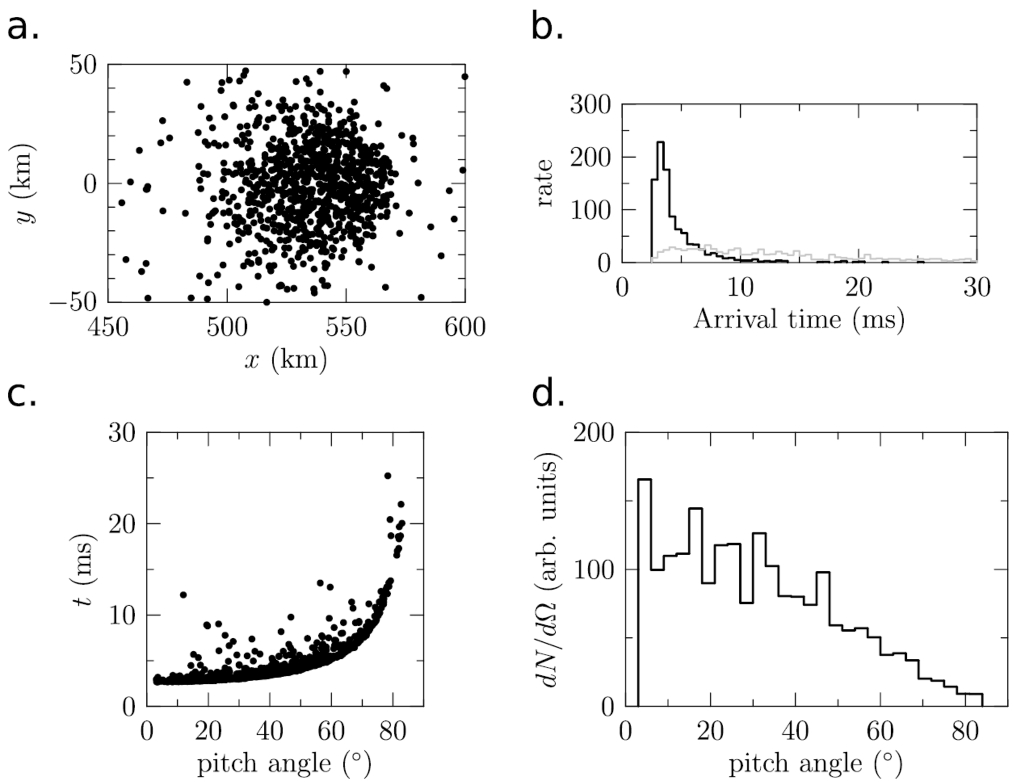


FIGURE 1. Results of simulations of properties of electrons emitted along with photons in a TGF. Properties shown when electrons first reach satellite altitude. a. distribution in plane at satellite altitude. b. arrival time distribution at satellite altitude (black), arrival time distribution spread out by a factor of 10 (grey). c. arrival time as a function of pitch angle. d. pitch angle distribution.

Observations [*Cohen et al*, 2010]

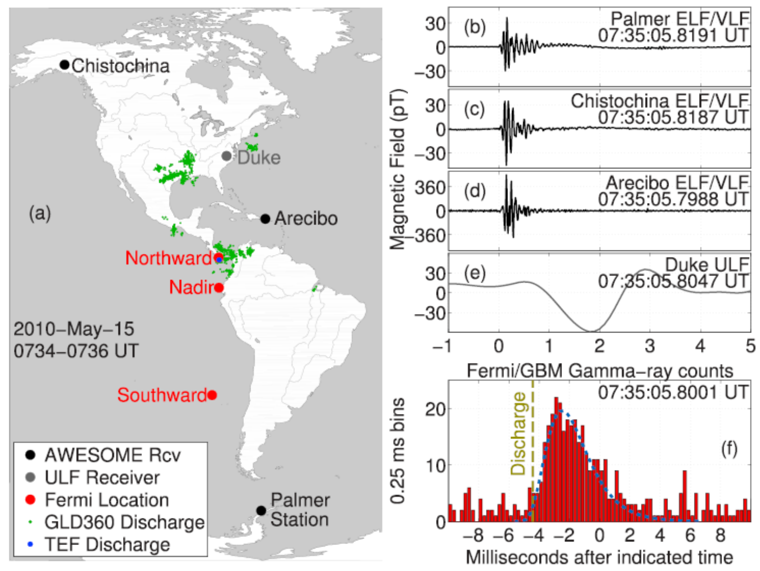


Figure 2. (a) Map with locations of Fermi (nadir, northern geomagnetic footprint, and southern geomagnetic footprint), GLD360 strokes (green dots), AWESOME receivers (black dots), ULF receiver (gray dot) and the TEF-associated discharge (blue dot) (b–d) Stanford AWESOME data at three receivers showing the TEF-associated radio atmospherics, (e) Duke ULF data showing the slower magnetic field development from the discharge. (Data are filtered to remove some low frequency interference below ~100 Hz.), (f) Fermi/GBM γ-ray data, in 0.25 ms bins, with the time of the lightning discharge (after correcting for 3.77 ms speed of light propagation delay) indicated with yellow stripe.

Outline

Neutron flux from TGFs

[*Carlson et al*, 2010]

- γ undergo photonuclear reactions, e.g. $^{14}\mathrm{N}(\gamma, n)^{13}\mathrm{N}$,
- giant dipole resonance at ~23 MeV, $\sigma_{pn} \sim 14$ mb (~5% of total γ cross-section)
- GEANT4 simulation predicts 10^{12} neutrons to be produced
- ~10 μs dispersion in arrival time to ground, ~50 ms to satellite
- ~0.5 km horizontal area radius on the ground, ~200 km at satellite

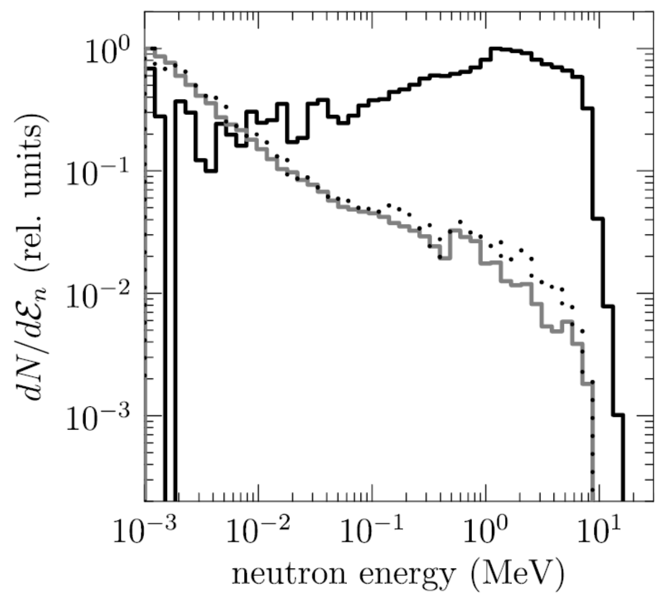


Figure 1. Characteristic energy spectrum of neutrons when produced (solid black curve). Also shown are the spectrum of neutrons reaching ground from a downward directed source at 2.5 km (black dotted) and satellite altitude from an upward directed source at 20 km (gray solid).

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Conclusions

- The electric fields which accelerate the runaway electrons may be caused by several mechanisms: (1) quasi-electrostatic fields produced after lightning discharges; (2) the electromagnetic pulses radiated by rapid lightning return strokes; and (3) the direct production of radiation by the lightning channel.
- Extreme parameters of lightning discharges are required for the first two mechanisms to produce the observed levels of TGF emissions
- Other mechanisms are probably at play, such as IC discharge [*Gurevich et al*, 2004] with positron/γ feedback [*Dwyer*, 2003].