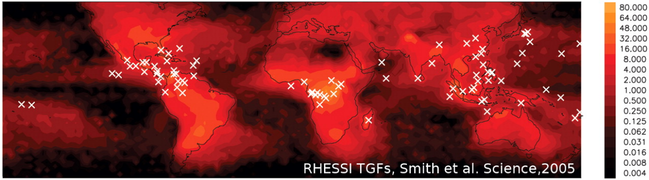
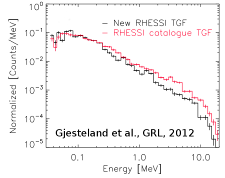
Introduction: Runaways electrons and TGFs

- C.T.R. Wilson 1925: Runaway electrons (**RE**), bremsstrahlung.
- Terrestrial gamma-ray flashes (**TGFs**): *Fishman et al., Science 264 (1994)*.
  BATSE: 76 detections of **TGFs** in 9 years.
  RHESSI: >500 detections (2004–2006).
- Possibly >50 **TGFs** per day (>3M lightning events).
- Source altitude < 20 km, energy of photons up to 20 MeV.
- **Accepted scenario**: bremsstrahlung of runaway electrons.

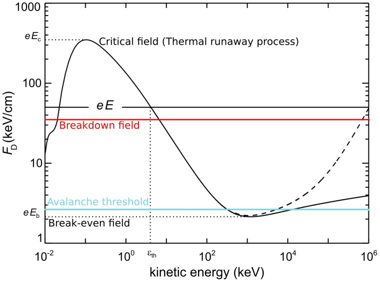


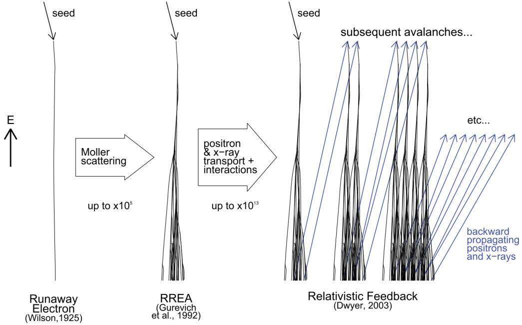


Detailed mechanism by which lightning is associated with TGFs is still a mystery.

Runaway electrons

- Dynamic friction force (Rate of energy loss): $\frac{\partial p}{\partial t} = eE - F$.
- Runaway electrons in air: Wilson 1925.
- Relativistic Runaway Electron Avalanche (**RREA**): Gurevich 1992;
- Relativistic feedback: Dwyer 2003 (Avalanche threshold $E_{th} = 2.84 \times 10^5$ V/m)

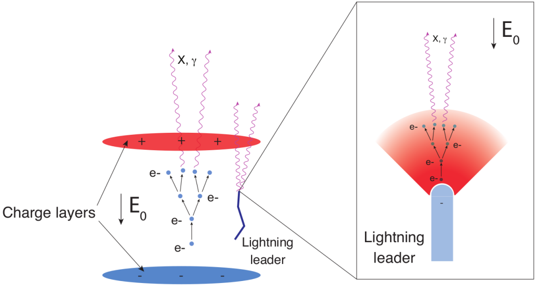




(*Fig. source: Dwyer et al., Space Sci Rev, 2012.*)

Two theories to explain TGFs

- Relativistic Runaway Electron Avalanche + Feedback (e.g., Dwyer)
  → high energy seed electron needed.
- Thermal runaway process (e.g., Moss 2006 , Chanrion 2008, 2014 , Li 2012, Celestin 2011).
  → **acceleration of electrons in streamer fields** (tens of kV).
  → further acceleration in the field of leaders (tens of MV).



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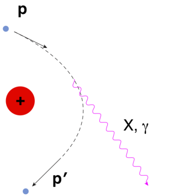


Bremsstrahlung emission process.

Needed: 10^{17} runaway electrons, >1MeV, (Dwyer, GRL, 2003).

Is the thermal runaway process from streamers able to provide enough of RE??

Introduction: What is a **streamer**?

Streamer breakdown theory (Loeb and Meek **1930'**)

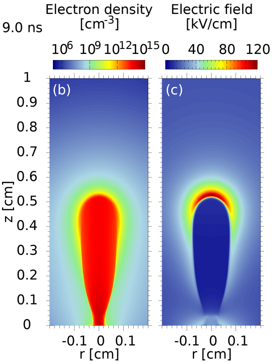
→ 'Fast' breakdown for spark discharge at atm pressure

→ Time scale $<10^{-7}$ s for one-cm gap:

ions too slow to be blamed;

(classical theory relied on secondary emission)

→ New concept: 'Streamers'



Streamers:

Contracted ionizing waves with self-generated field enhancement that propagates into a low-ionized medium exposed to high electric field leaving filamentary trails of plasma behind.

Characteristics:

Velocity even 1% speed of light;

Radius typically 10^{-4}–10^{-3}m at STP;

Peak electric field at Streamer head SH (net space charge): 4–7 E_k ($E_k \sim$ 32 kV/cm at STP)

⇝ **Intense electron impact ionization**: space charge region move forward;

Polarity (sign of charge in the streamer head):

→ **(+) Positive**: propagate. against electron drift: need of ambient seed charges

→ **(−) Negative**: el. aval. from SH ⇝ propagate w/o need of seed electrons

[R. V. Hodges, 1985 Phys. Rev. A; Raizer, 1991; V. Pasko 2006, U. Ebert 2006 PSST]

Introduction: Why are streamers interesting?

C.T.R. Wilson (**1925**): Possibility of large scale discharges high above thunderclouds.

if(

The dipole electric field of the thunderclouds falls with altitude as $1/h^3$.

.and.

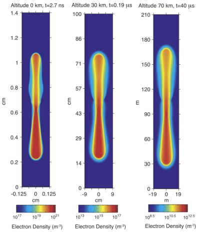
Critical breakdown field falls exponentially with decreasing air density.

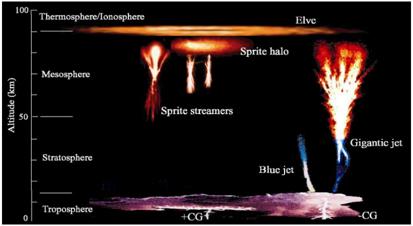
)then

There must be an altitude high above where the electric force would exceed the sparkling limit.

endif

Double headed streamers $\rightsquigarrow$ precursors to more complicated phenomena.





[V.P. Pasko PSST 2007] [credits: cnes]

Since 1989 many **T**ransient **L**uminous **E**vents discovered.

But streamers play a role even for more unusual phenomena!

Modeling of streamers: Classical fluid model

How to model the streamer discharge?
It depends on the physical question we want to address!
Basic ingredients [U. Ebert, PSST, 2006; A. Luque, U. Ebert, JCP 2012]:

(1) Ionization processes (electron impact, photons)
(2) Drift and diffusion of charged particles in electric field
(3) Effects of a space charge on the electric field

'Classical' fluid streamer model:

$$\partial_t n_s - \mathrm{sign}(q_s)\nabla \cdot (n_s\, \boldsymbol{v}_s) - \nabla \cdot (D_s\, \nabla n_s) = S_s,$$
$$\varepsilon_0 \nabla^2 \varphi = \sum_s q_s n_s, \quad s \in \{\text{charged species}\}.$$

Approximations:

(a) Density Approximation: distribution of charged species described with densities
(b) Local Field Approximation: Electrons relax rapidly enough $\rightsquigarrow$ in equilibrium with **E** at given place.
(c) Electrostatic Approximation: Induced electric fields are negligible ($\mathbf{E} = -\nabla\varphi$).

Challenges: spatial and time scales span many orders of magnitude.

Classical model is not sufficient to study electron acceleration!

Hybrid model

A beam-bulk approach proposed by Belenguer and Boeuf for RF discharge (Phys. Rev. A, 1990).
Model combines 2 models for 2 electron groups divided in the energy space:

Electrons below 100 eV

Axisymmetric fluid streamer model in a point to plain geometry
[Pecherau2012,Celestin2009]

- Classical drift-diffusion model based on [Kulikovsky1997]
- The mobility, diffusion coefficient and reaction rates are calculated from Monte Carlo model for electrons of energy below 100 eV.
- Electric field is calculated solving the Poisson equation

Electrons above 100 eV

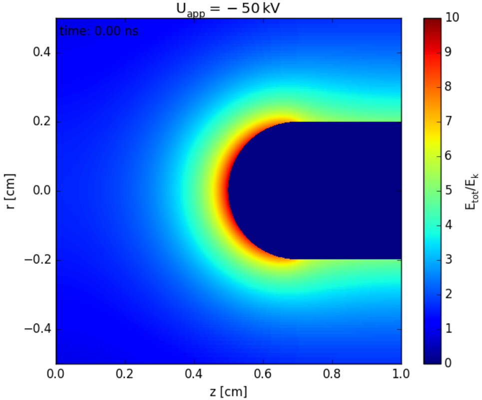
2D-s,3D-V PIC-MCC model

- Standard PIC-MCC code follows the electron trajectories in the electric field and their collisions with neutral air molecules [Chanrion, JCP, 2008] .
- Injection of electrons Fluid $\rightarrow$ PIC based on fluid macroscopic parameters using precomputed distribution functions.
- Electrons that slow below 100 eV are reinjected in the fluid model.

• Coupling between the two models is repeated every time step.

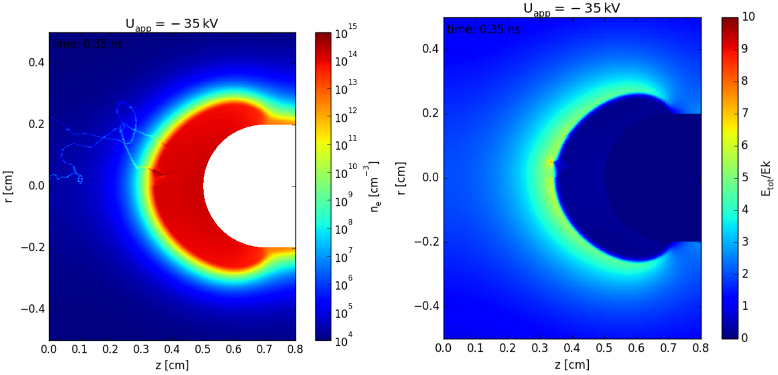
Test case

- Hemisphere pin electrode (0.2 cm radius).
- 0.5 cm gap.
- Applied voltage: (**negative polarity**) step function with amplitude: $\{-35, -45, -50 kV\}$
- Air at atmospheric pressure
- Low preionization of 10^4 cm^{-3}

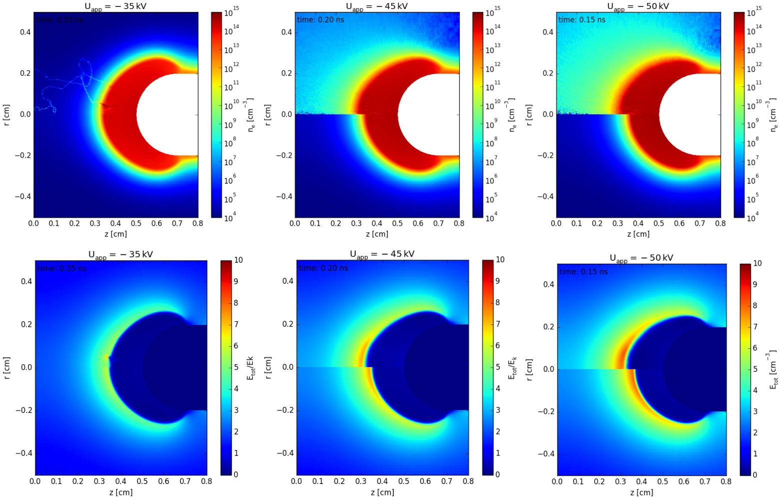


Photoionization not included: to accent the role fast electrons

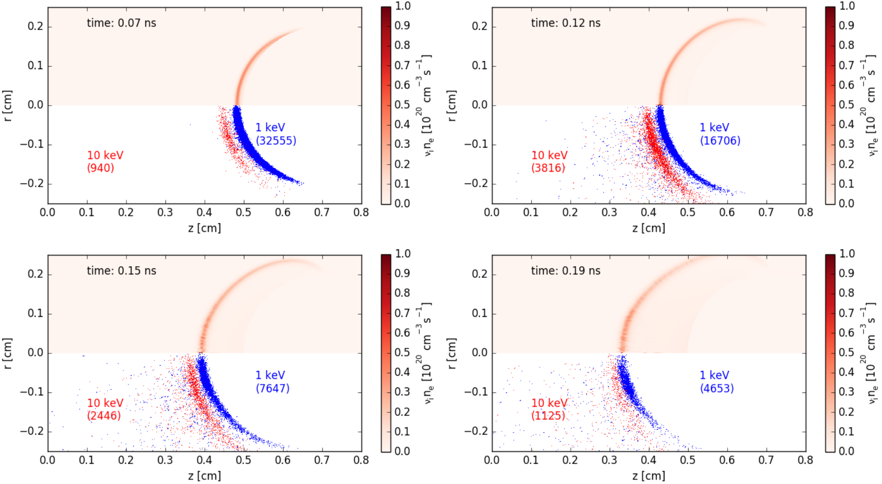
Effect of fast electrons on discharge: -35kV



Effect of fast electrons on discharge



RE acceleration source



Electron acceleration: z-energy space