# Branching Streamers as a Source of Thermal Runaway Electrons

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- Introduction
  - Observations of X-Ray and Gamma-Ray Radiation Associated with Lightning
  - Streamers and High-Energy Radiation
  - Dynamic Friction Force of Electrons in Air
  - Motivation for the Present Study
- Model Formulation
  - Monte Carlo Model
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- Model Results
  - Validation of Monte Carlo Model
  - Acceleration and Expansion of Streamers
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  - Pre-Branching State of a Negative Streamer
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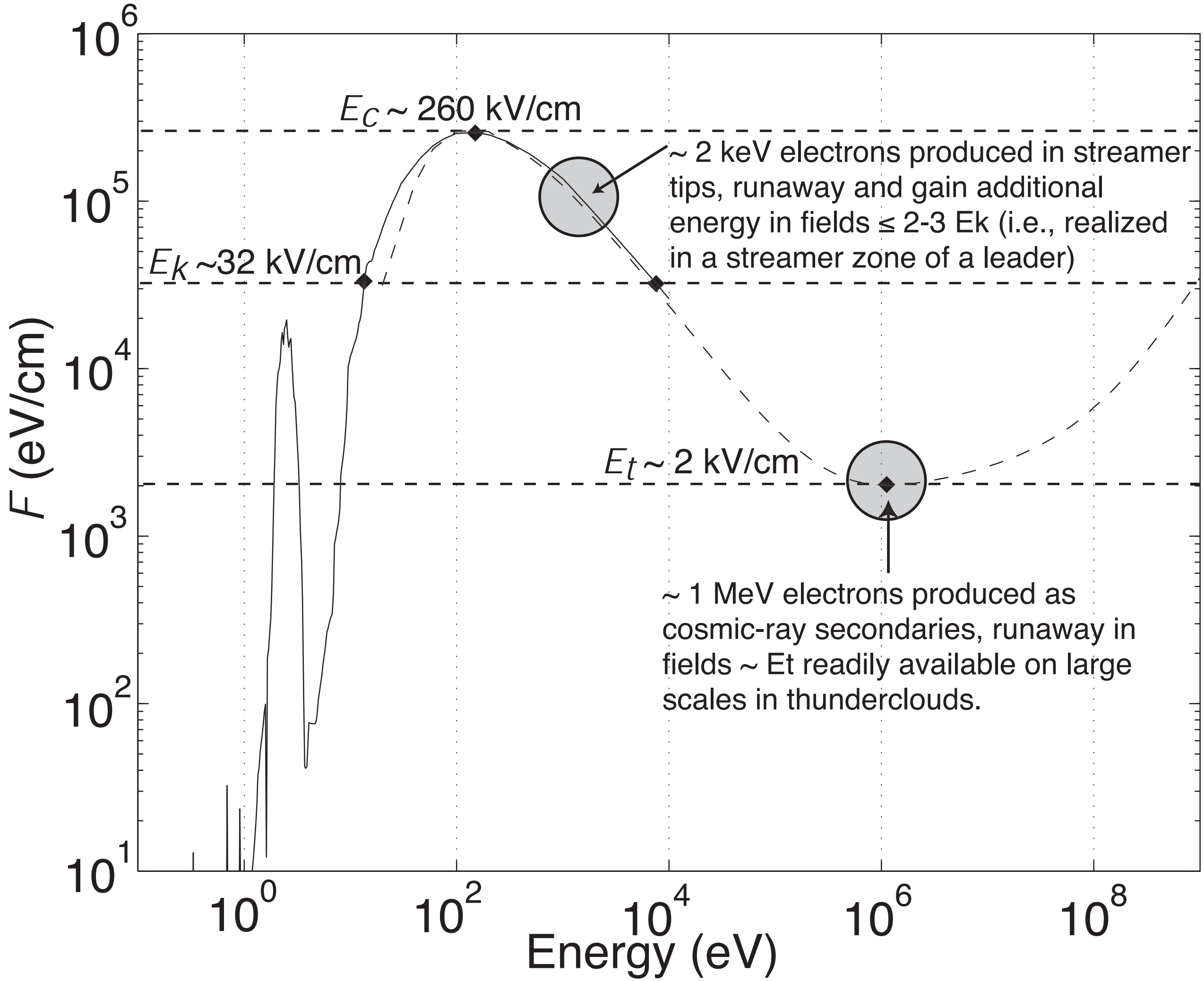
## Observations of X-Ray and Gamma-Ray Radiation Associated with Lightning

- Terrestrial gamma-ray flashes (TGFs) have been detected from space by the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory [*Fishman et al.*, Science, 264, 1313, 1994].
- Measurement results from the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) further show the TGF events can reach extremely high energies ($> 10$ MeV) [*Smith et al.*, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract AE53A-10, 2004].
- X-ray emissions have been observed during the approach to ground stage of natural lightning [*Moore et al.*, GRL, 28, 2141, 2001].
- High-energy radiation from dart leaders in triggered lightning discharges has been reported by *Dwyer et al.* [Science, 299, 694, 2003; GRL, 31, L05118, 2004].
- Recent time-resolved observations of X-ray emissions from lightning indicate that intense X-ray bursts are emitted in coincidence with the formation of the leader steps [*Dwyer et al.*, Geophys. Res. Lett., 32, L01803, 2005].

## Streamers and High-Energy Radiation

- The acceleration of electrons in tips of highly overvolted streamers propagating in electric fields $\sim 3E_k$ [*Babich,* Sov. Phys. Dokl., 27, 215, 1982; and references therein], where $E_k$ is the conventional breakdown threshold field, has been proposed for interpretation of X-ray radiation observed in experiments reported by *Tarasova et al.* [Sov. Phys. Tech. Phys., 19, 351, 1974].
- It has also been proposed that the high electric fields in streamer tips can accelerate electrons to energies of several keV, initiating electron runaway in relatively low ambient electric fields $E \sim E_k$ [*Pasko et al.*, GRL, 25, 2123, 1998, and references cited therein].
- The X-ray radiation from lightning leaders may be related to the enhancement of electric field in the leader streamer zone [*Dwyer et al.*, GRL, 31, L12102, 2004] leading to the generation of runaway electrons in streamer tips.


$E_C$ ~ 260 kV/cm
$E_k$ ~32 kV/cm
$E_t$ ~ 2 kV/cm
~ 2 keV electrons produced in streamer tips, runaway and gain additional energy in fields ≤ 2-3 Ek (i.e., realized in a streamer zone of a leader)
~ 1 MeV electrons produced as cosmic-ray secondaries, runaway in fields ~ Et readily available on large scales in thunderclouds.
F (eV/cm)
Energy (eV)
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$
$10^6$
$10^0$
$10^2$
$10^4$
$10^6$
$10^8$

## Motivation of the Present Study

- Two possible sources of runaway electrons:
  - MeV electrons produced as cosmic-ray secondaries
  - Several keV electrons accelerated from low energies in streamer tips
- The quantitative calculation of fluxes of thermal runaway electrons generated in streamer tips represents an outstanding problem, which may be relevant to recently observed energetic radiation from lightning and to gamma-ray flashes of terrestrial origin.

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## Monte Carlo Model

- In order to study electron runaway phenomena, a Monte Carlo model has been developed, which is capable of describing electron dynamics in air under influence of an external electric field of arbitrary strength [*Moss et al.*, Eos Trans. AGU, 85(47), Fall Meet. Suppl., Abstract AE31A-0158, 2004].
- The model is similar in technical details to the model previously developed for $N_2$ by *Tzeng and Kunhardt* [Phys. Rev. A, 34, 2148, 1986] and *Kunhardt and Tzeng* [Phys. Rev. A, 34, 2158, 1986], and incorporates the following features:

  (1) the "null collision method" to determine time between collisions;

  (2) the remapping of the electron assembly to improve statistics for the high-energy tail of the electron distribution;

  (3) the differential ionization and scattering cross sections for realistic description of energy spectrum of secondary electrons and the forward scattering properties of electrons at high energies.

## Streamer Model

- The dynamics of a streamer is described by the electron and ion convection-diffusion equations coupled with Poisson's equation in a cylindrical coordinate system [e.g., *Liu and Pasko*, JGR, 109, A04301, 2004]:

$$\begin{aligned}
\frac{\partial n_e}{\partial t} + \nabla \cdot n_e \vec{v}_e - D_e \nabla^2 n_e &= (\nu_i - \nu_{a2} - \nu_{a3}) n_e - \beta_{ep} n_e n_p + S_{ph} & (1) \\
\frac{\partial n_p}{\partial t} &= \nu_i n_e - \beta_{ep} n_e n_p - \beta_{pn} n_n n_p + S_{ph} & (2) \\
\frac{\partial n_n}{\partial t} &= (\nu_{a2} + \nu_{a3}) n_e - \beta_{pn} n_n n_p & (3) \\
\nabla^2 \phi &= -\frac{e}{\epsilon_0}(n_p - n_e - n_n) & (4)
\end{aligned}$$

- The coefficients of the model are assumed to be functions of the local electric field and obtained from solutions of the Boltzmann equation.

- The photoionization process is accounted for by using a physical model proposed by *Zheleznyak et al.* [High Temp., 20, 357, 1982].

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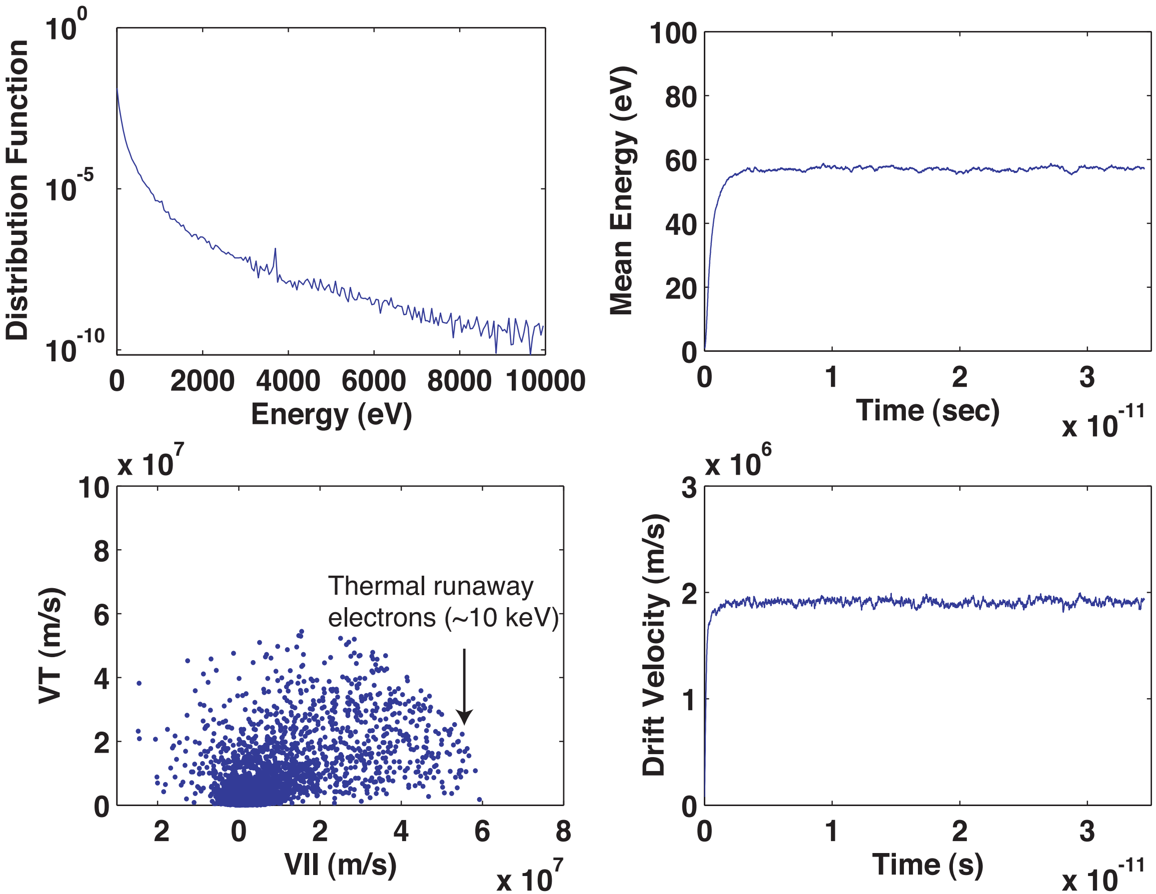
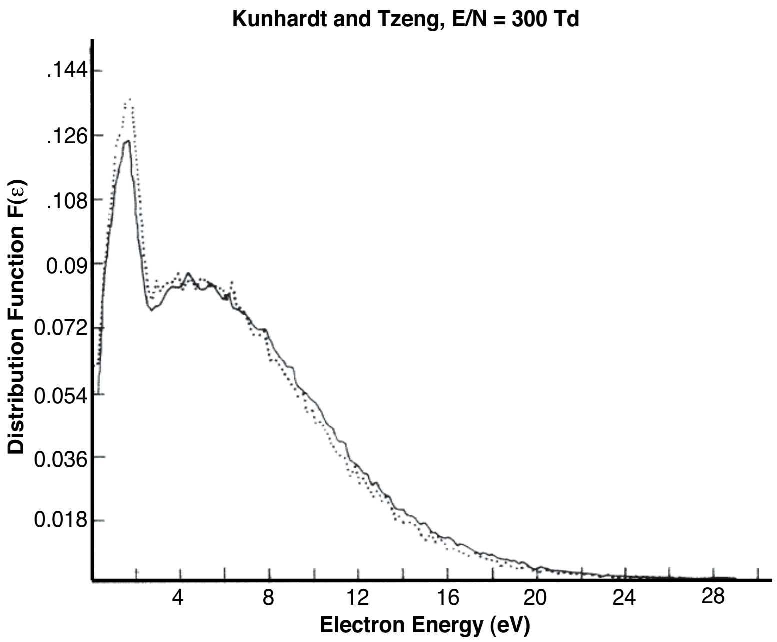
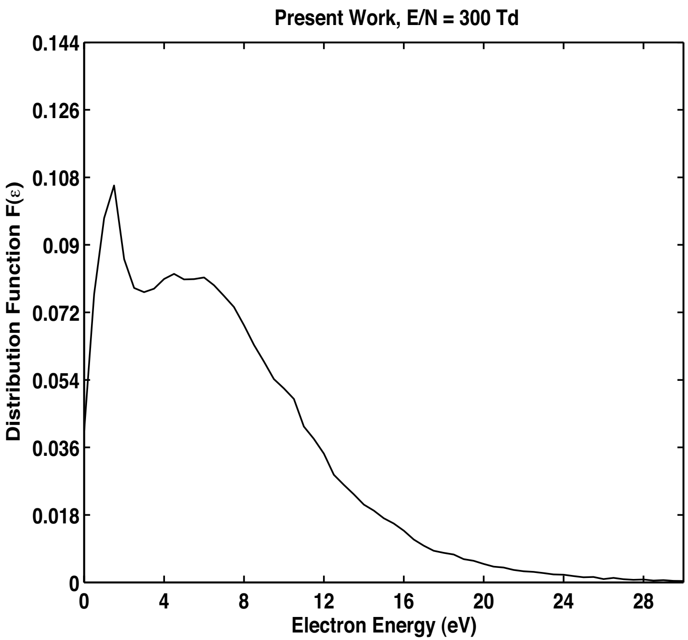
# Electron Energy Distribution in Air at $E = 20E_k$



## Electron Energy Distributions in $N_2$

- Comparison of the Monte Carlo modeling results of electron energy distribution in $N_2$ at E/N = 300 and 1500 Td with those presented by *Kunhardt and Tzeng* [Phys. Rev. A, 34, p. 2161, 1986].



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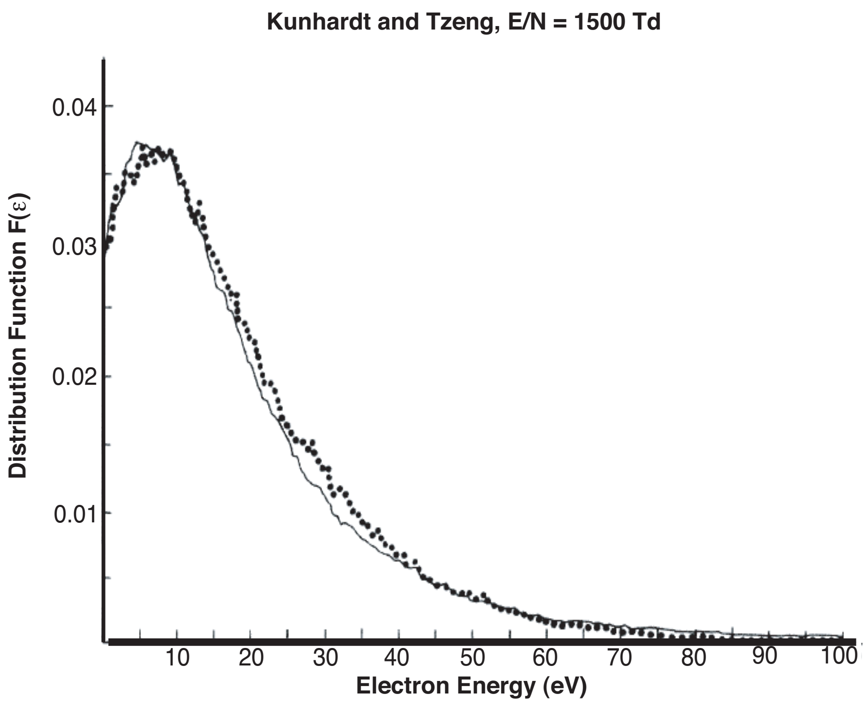


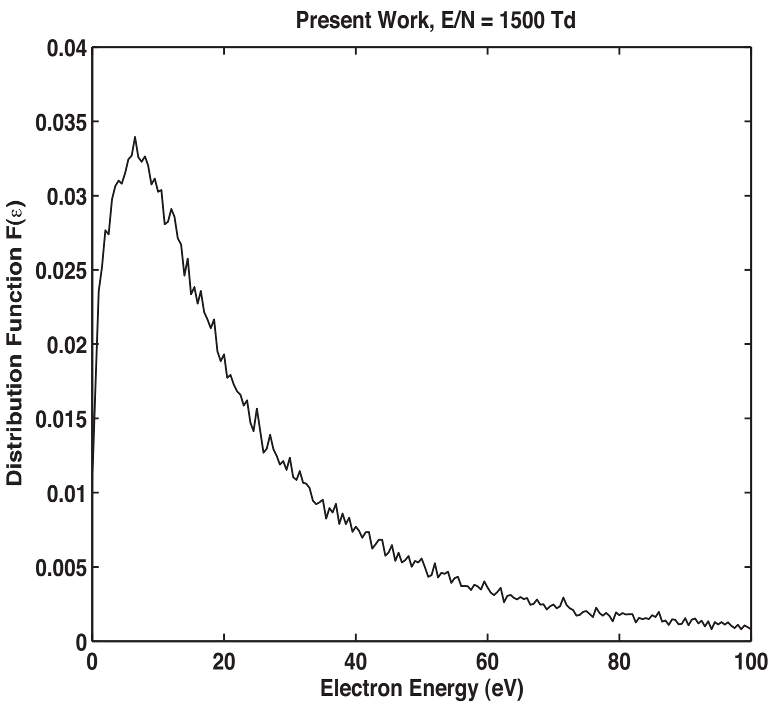

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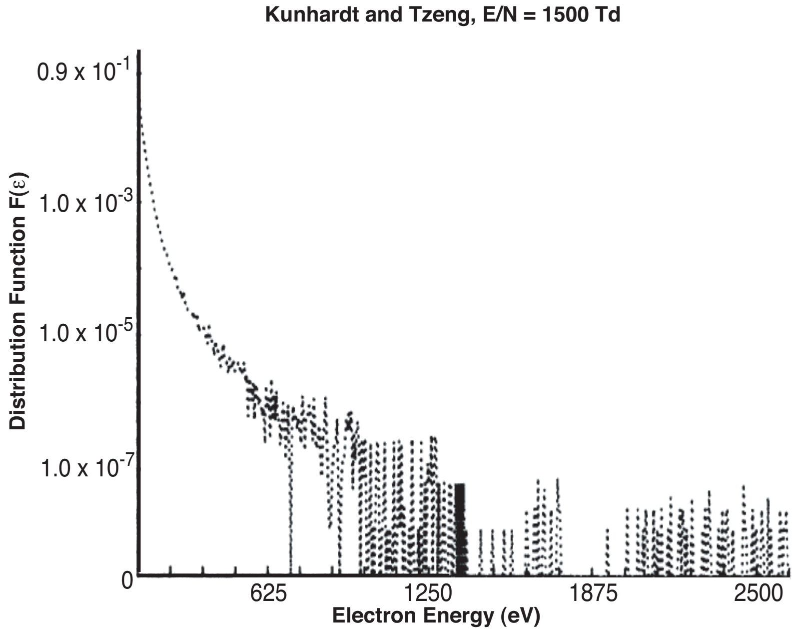
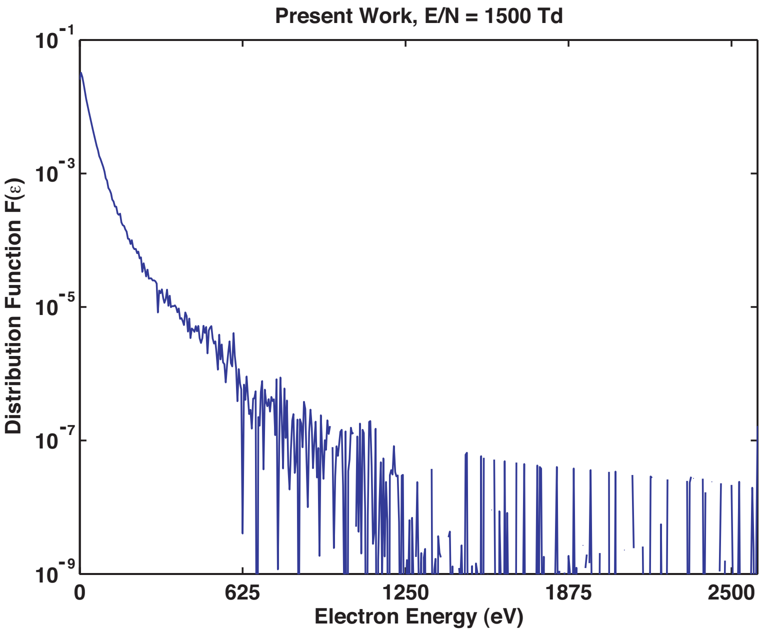
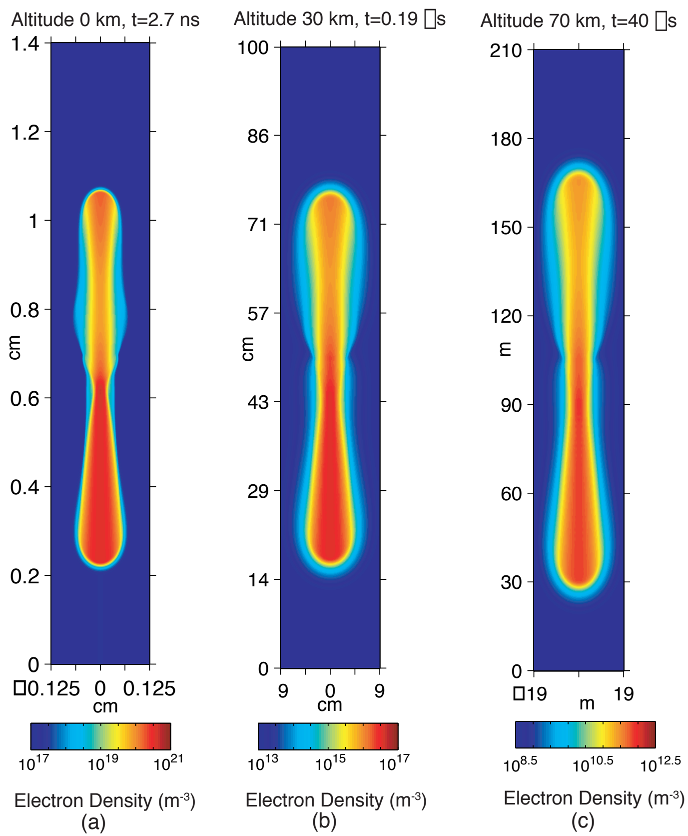


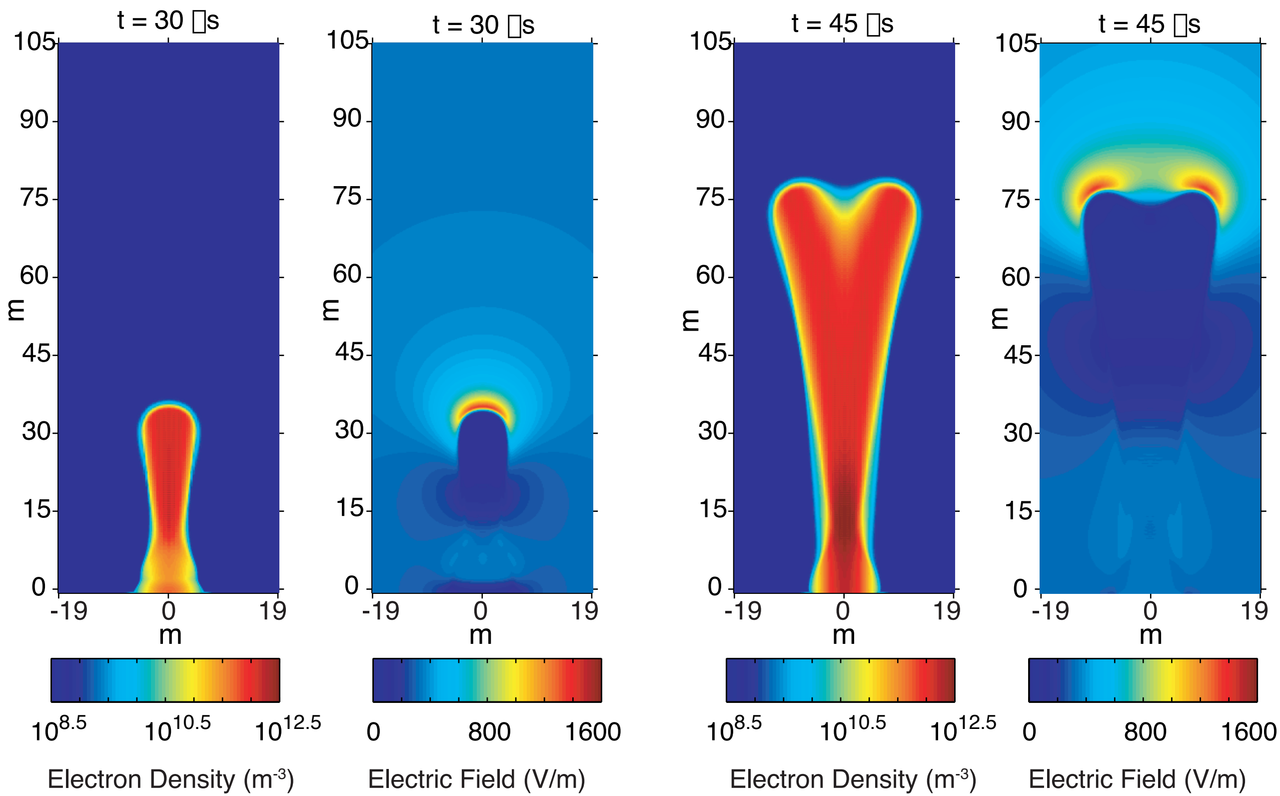



# Acceleration and Expansion of Streamers

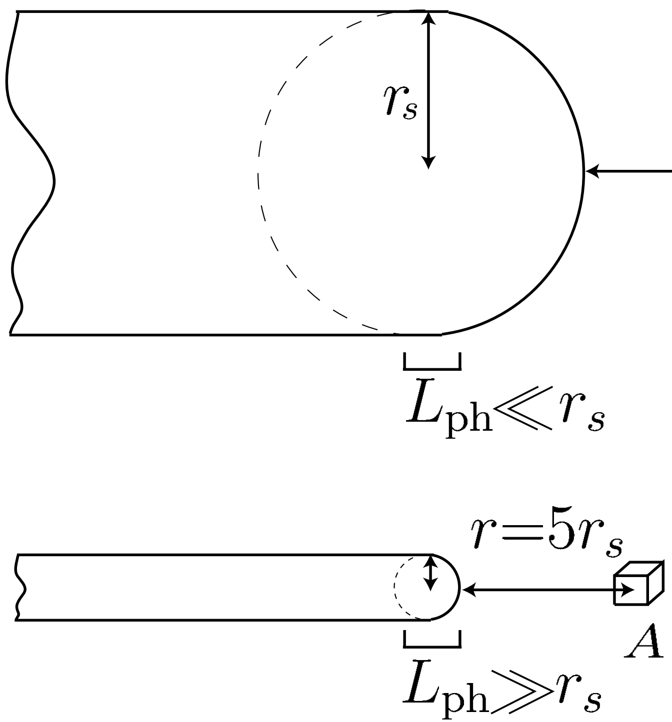
- Results of model calculations of double-headed streamers developing from single electron avalanches in a homogeneous electric field, $E = 1.5E_k$.



# Branching of Positive Streamers



# Physical Mechanism of Streamer Branching

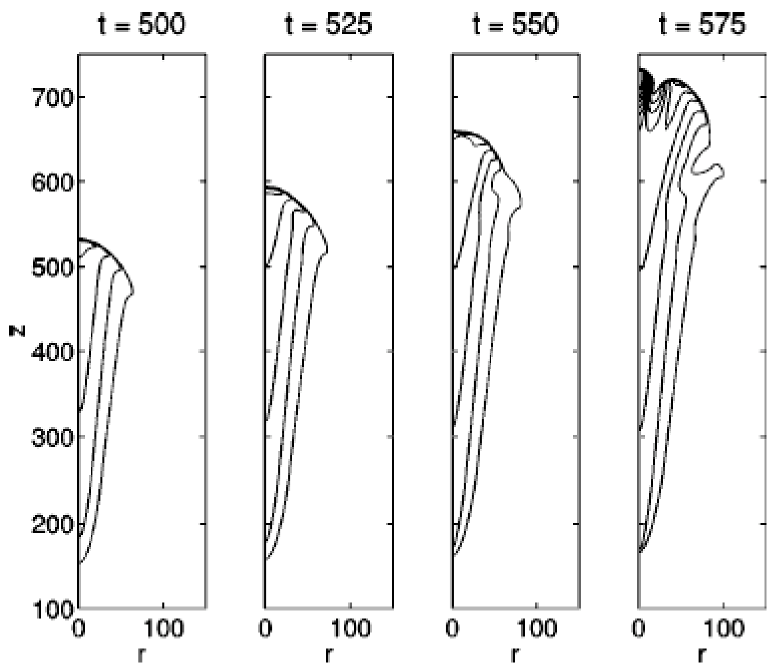



$$\frac{dQ_{\mathrm{ph}}(A')}{dV_2} \ll \frac{dQ_{\mathrm{ph}}(A)}{dV_2}$$

- The photoionization range $L_{\mathrm{ph}}$ remains constant for expanding streamers.
- Streamers branch when the streamer radius $r_s$ exceeds $L_{\mathrm{ph}}$.

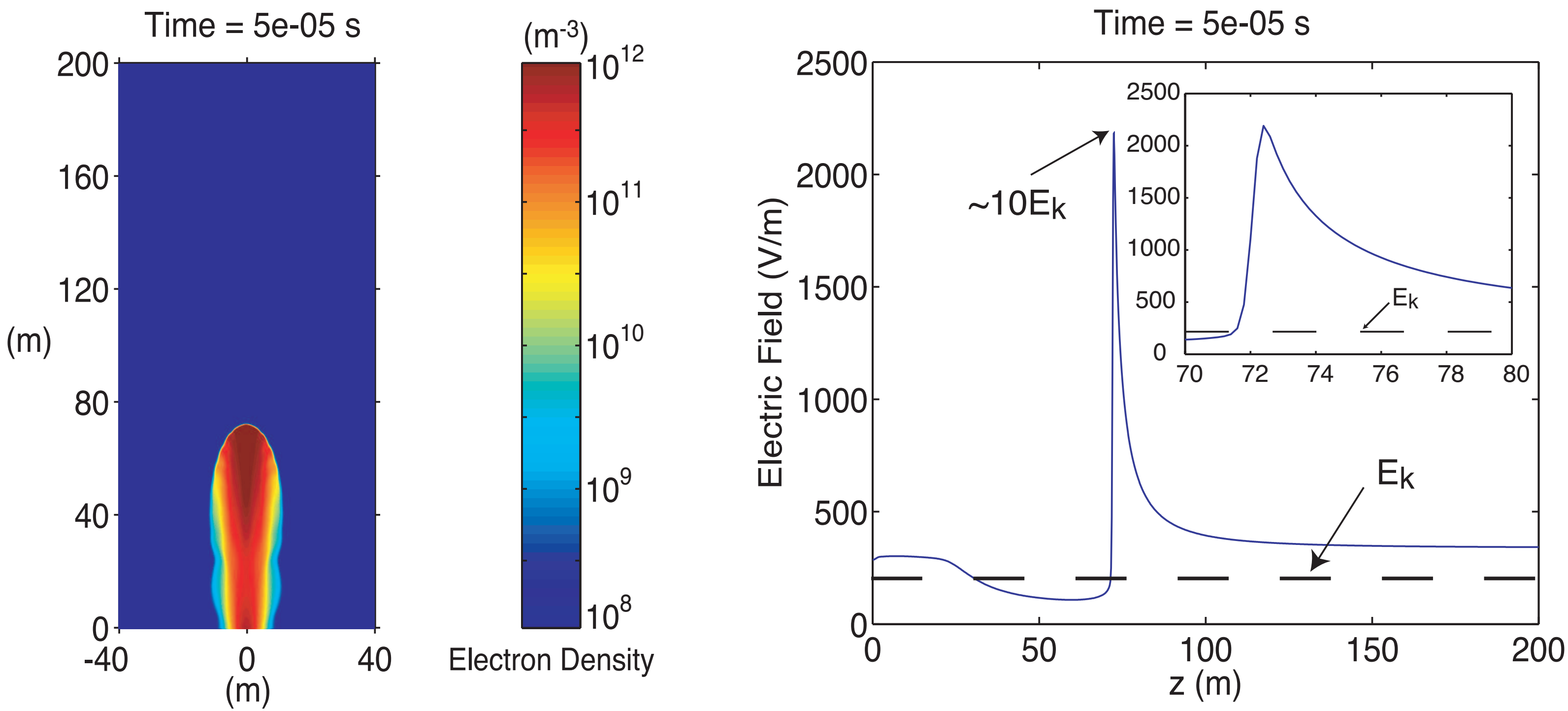
## Branching of Negative Streamers

- It has been demonstrated that negative streamers developing in high ambient fields (100 kV/cm at ground pressure), when no preionization available ahead of the streamer, are reaching an unstable "ideal conductivity" state leading to branching of the streamer [*Arrayas et al.*, Phys. Rev. Lett., 88, 174502(R), 2002; *Rocco et al.*, Phys. Rev. E, 66, 035102(R), 2002].



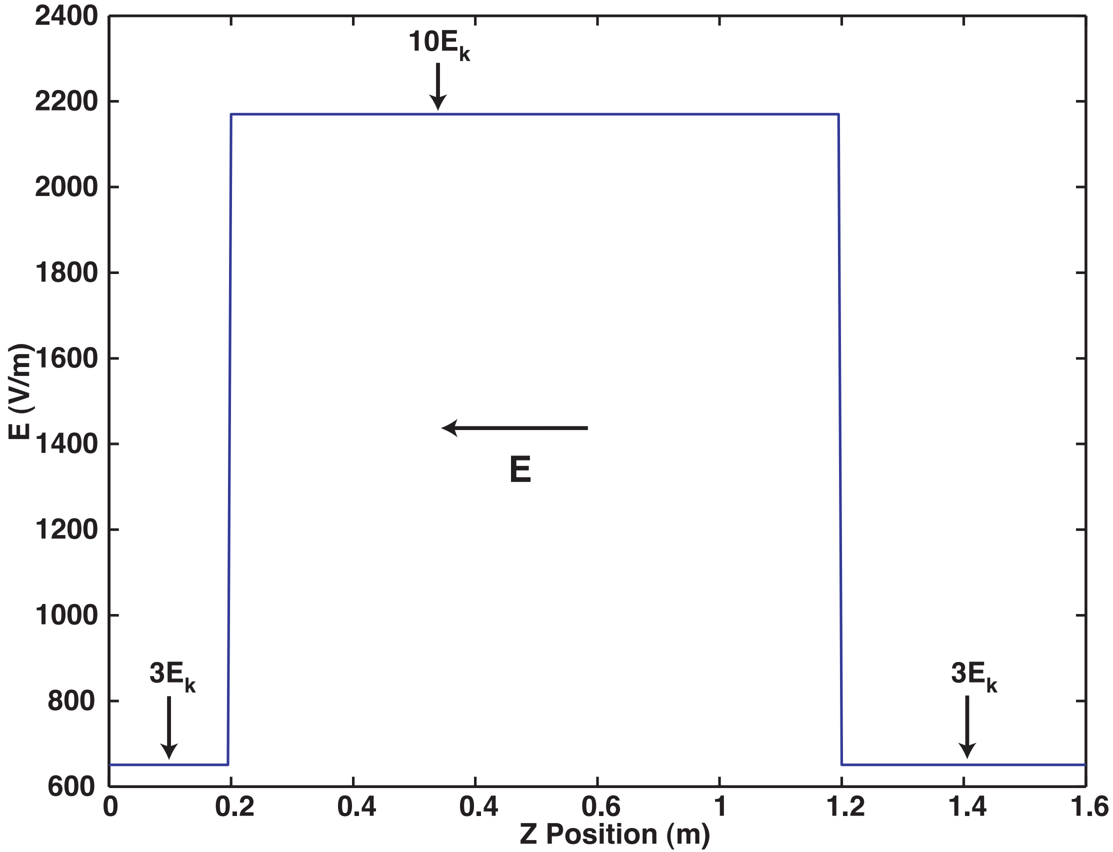
# Pre-branching State of a Negative Streamer

- A negative streamer propagating at an altitude of 70 km in an ambient electric field of $1.5E_k$ with no preionization available ahead of the streamer. At the moment of time .05 ms, the streamer reaches an unstable state preceding branching of the streamer, which is associated with a very large electric field in the streamer head.



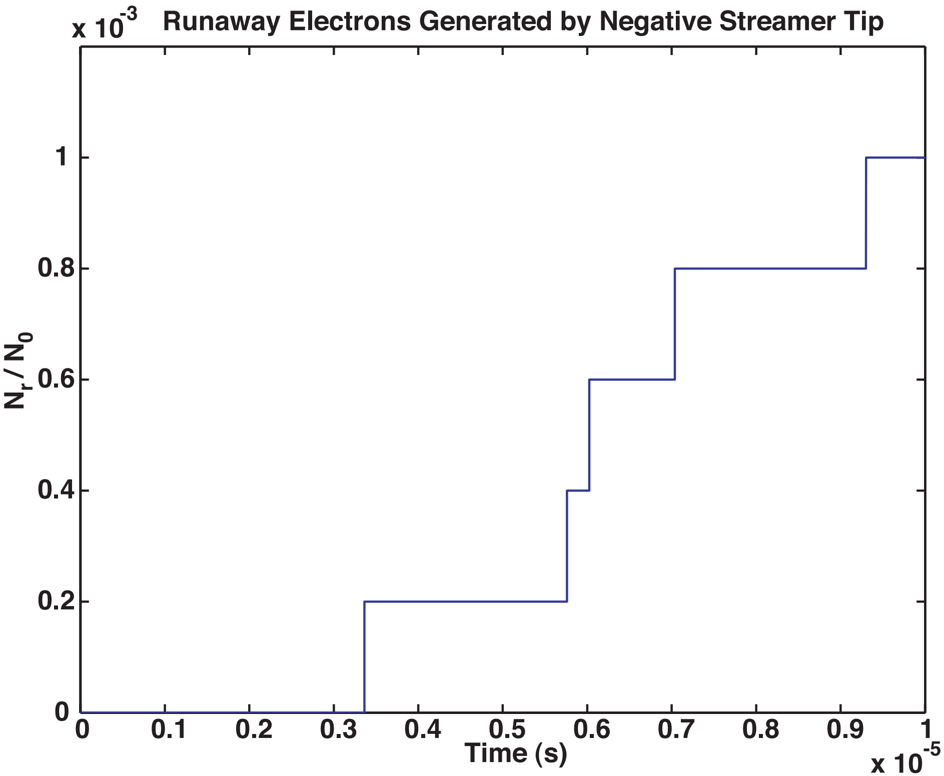
## Runaway Electron in the Streamer Tip [*Moss et al.*, 2004]

- The electric field around the tip of a negative streamer in a pre-branching state at 70 km is approximated by a square pulse of 1 m in width.



## Runaway Electron in the Streamer Tip [*Moss et al.*, 2004]

- An initial assembly of $N_0 = 5000$ electrons with an energy of 1 eV is placed in the approximated field distribution. $N_r$ is defined as the number of electrons moving out of the simulation domain through right boundary with an energy greater than 1 keV (energy required for an electron to runaway in a field of $3E_k$). The following figure illustrates the fraction $N_r/N_0$ as a function of time.



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# Conclusions

- The acceleration and expansion of streamers propagating in strong electric fields result in the reduction of the preionization level ahead of the streamer. To compensate the reduction in preionization level, the magnitude of the electric field in the streamer tip reaches a value as large as $10E_k$ at the stage immediately preceding the branching.
- The extremely high field in the streamer tip generated during the pre-branching stage can accelerate a fraction of low-energy electrons in the streamer tip to energies of several keV. Depending on electric field configuration, these electrons can runaway and continue gaining energy in ambient fields $\leq$ 2-3$E_k$.
- We propose that streamers can be a robust source of runaway electrons responsible for recently observed energetic radiation from lightning and for gamma-ray flashes of terrestrial origin.