The Physics of Sprites: Current Studies in North America

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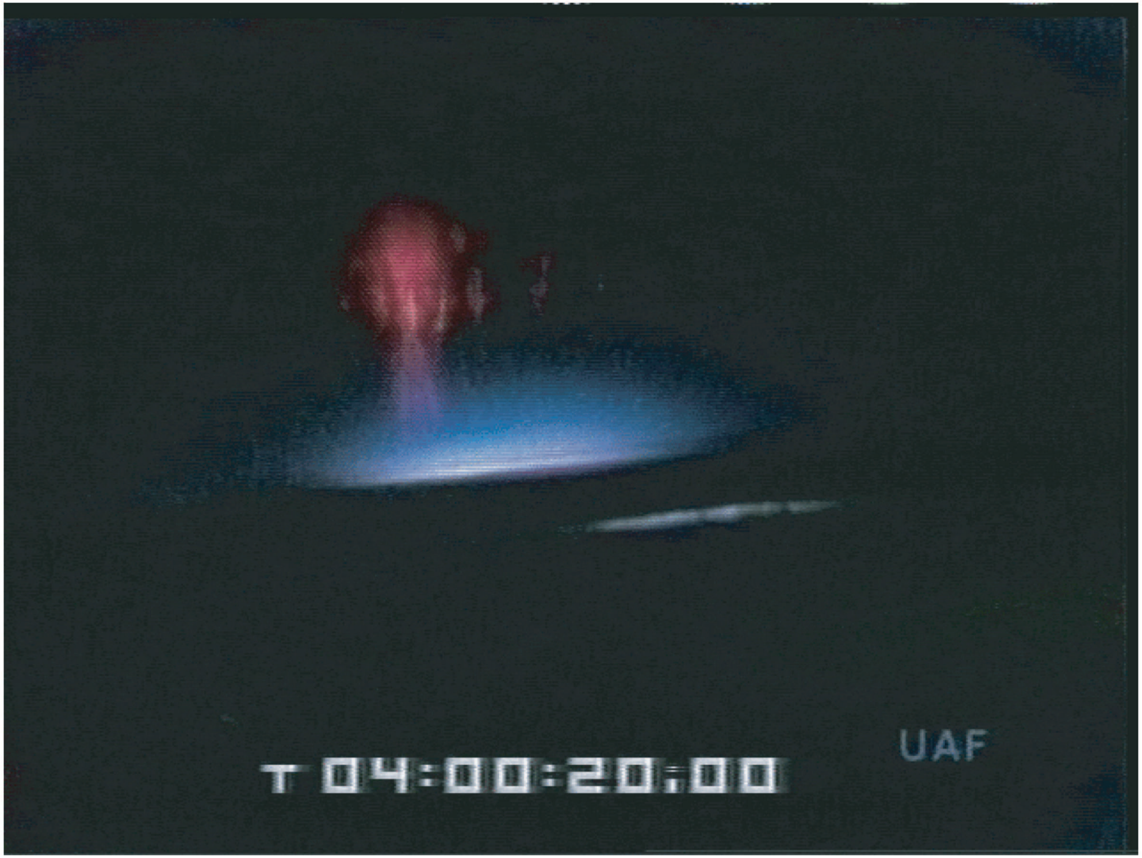
- General Morphology
- Physical Mechanism of Sprites
- Large-Scale Modeling of Sprites
- Modeling of Sprite Streamers

First Image of Unusual Optical Flashes Above Thunderstorms

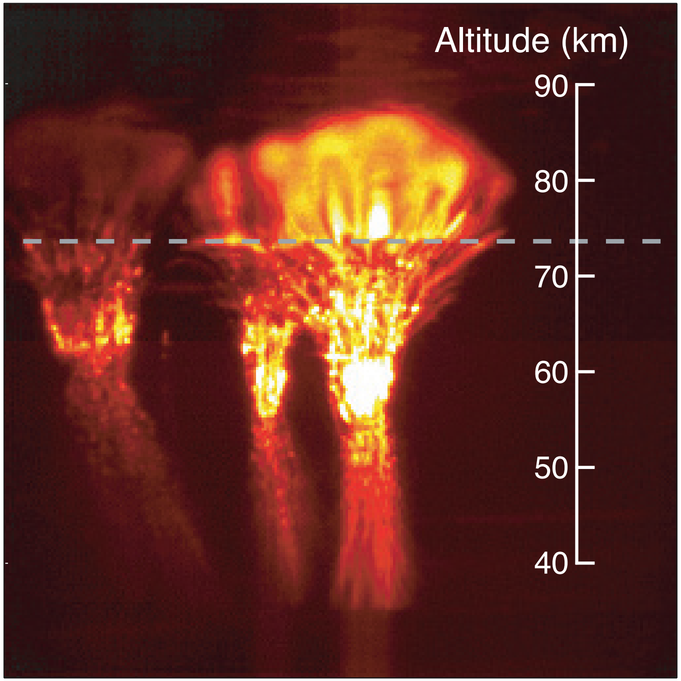
- This image was obtained serendipitously on July 5, 1989 during a test of a low-light-level TV camera at the O'Brien Observatory of the University of Minnesota [*Franz et al.*, Science, 249, 48, 1990].

First Color Image of Sprites

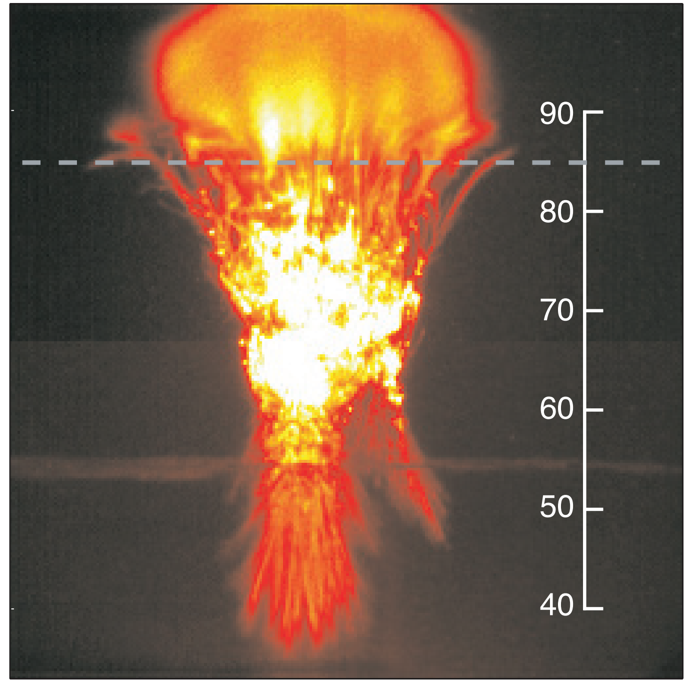


- The event was recorded on 4 July 1994 at 0400:20 UT during Sprites94 aircraft campaign [*Sentman et al.*, Geophys. Res. Lett., 22, 10, 1205, 1995].

Vertical Altitude Structuring in Sprites



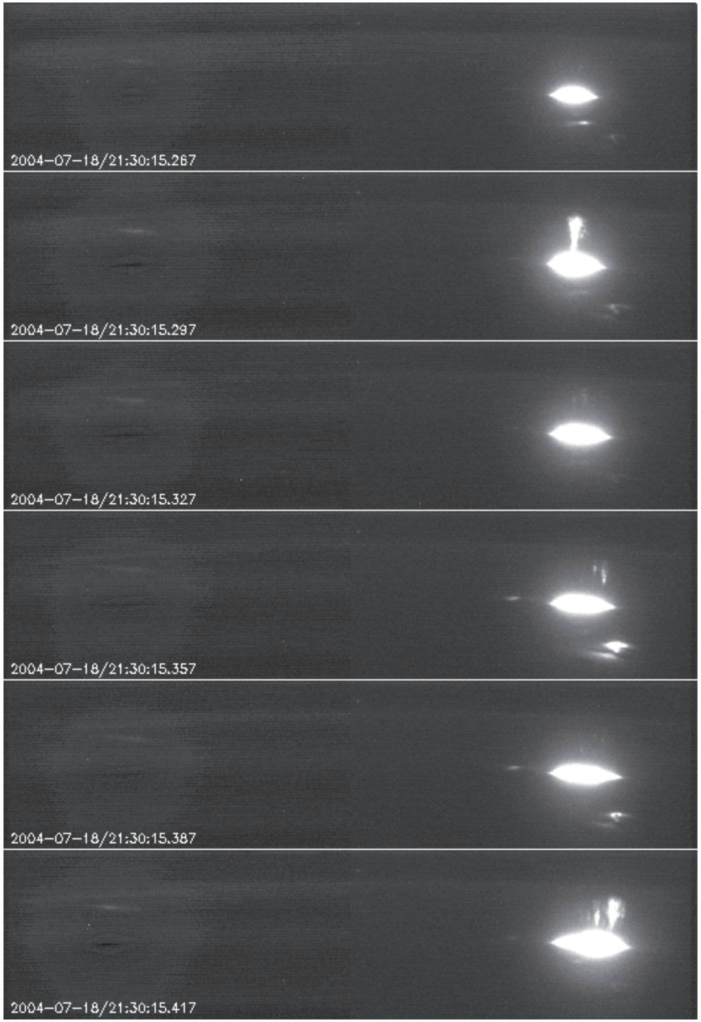
04:36:09.230 UT

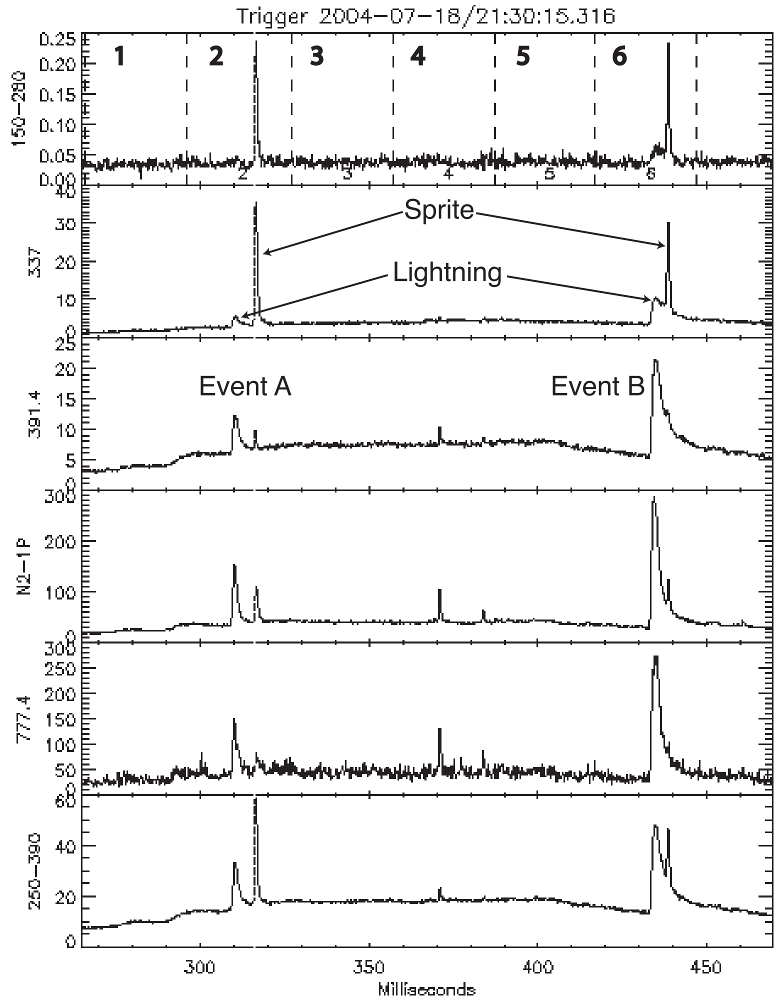


05:24:22.804 UT

- Sprites often appear relatively homogeneous at their top but highly structured at their bottom [*Stenbaek-Nielsen et al.*, Geophys. Res. Lett., 27, 3829, 2000; *Pasko and Stenbaek-Nielsen*, Geophys. Res. Lett., 29, 10, L014241, 2002].

Sprites Recorded by ISUAL on FORMOSAT-2 Satellite [*Mende et al.*, 2004]





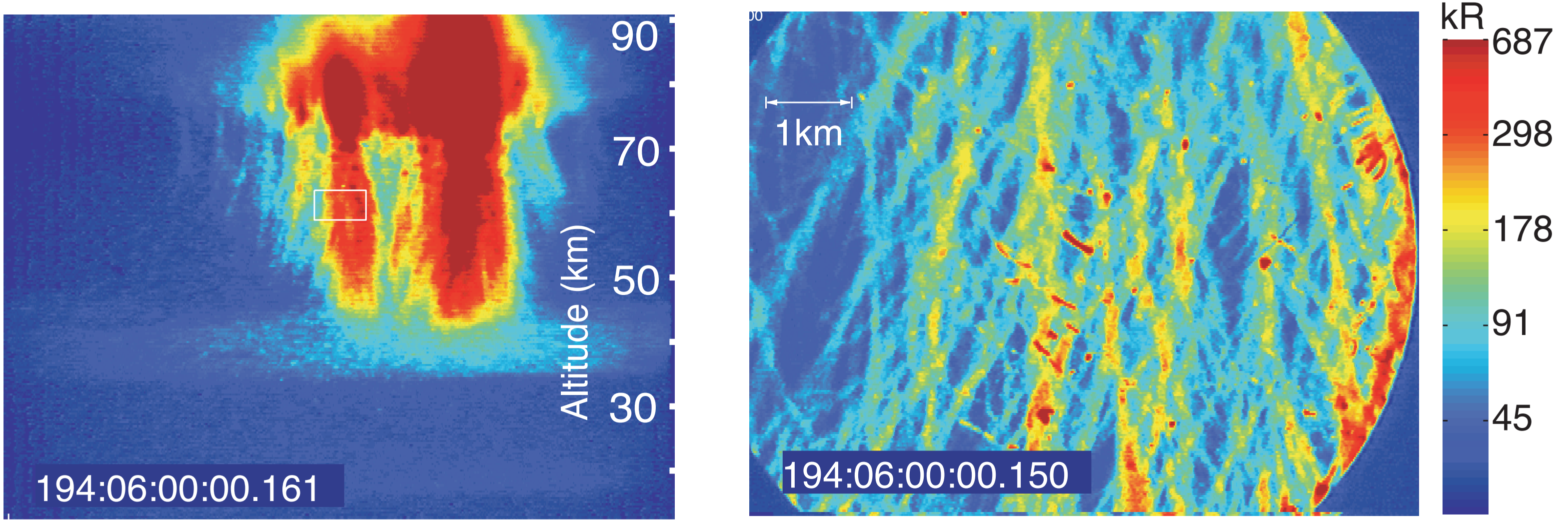
Summary of Emissions from Sprites

- Dominant emission band systems from sprites:

Emission Band System	Transition	Excitation Energy Threshold (eV)	Lifetime at 70 km Alt.	Quenching Alt. (km)
$1PN_2$	$N_2(B^3\Pi_g)\rightarrow N_2(A^3\Sigma_u^+)$	$\sim$7.35	5.4 μs	$\sim$53
$2PN_2$	$N_2(C^3\Pi_u)\rightarrow N_2(B^3\Pi_g)$	$\sim$11	50 ns	$\sim$30
LBH N_2	$N_2(a^1\Pi_g)\rightarrow N_2(X^1\Sigma_g^+)$	$\sim$8.55	14 μs	$\sim$77
$1NN_2^+$	$N_2^+(B^2\Sigma_u^+)\rightarrow N_2^+(X^2\Sigma_g^+)$	$\sim$18.8	69 ns	$\sim$48

- NO-γ emissions
  - The transition leading to NO-γ emissions:
    $$NO(A^2\Sigma^+) \rightarrow NO(X^2\Pi_r) + h\nu.$$
    The excitation energy threshold for $NO(A^2\Sigma^+)$ is 5.45 eV.
  - The NO-γ emissions from sprites are not observable for a wide bandwidth photometer. However, a photometer with a passband of 240–260 nm may be able to detect sprite NO-γ emissions from space [*Liu and Pasko*, 2007].

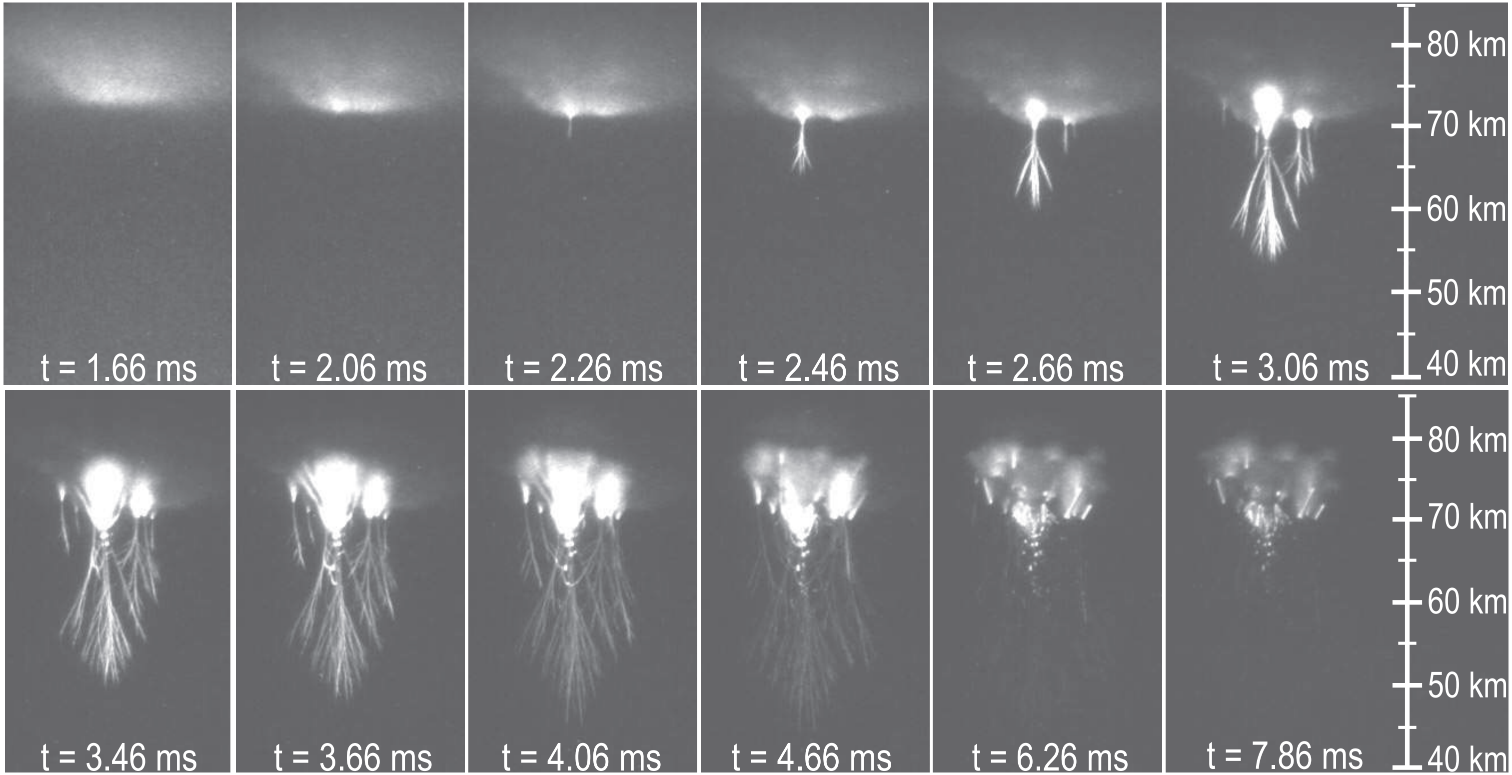
Telescopic Imaging of Sprites



- Wide and narrow field of view images of a bright sprite event [*Gerken et al.*, Geophys. Res. Lett., 27, 2637, 2000].
- The filamentary structures are the same phenomena known as streamer discharges at near atmospheric pressure.

High Speed Imaging of Sprites

- High speed sprite images with ∼0.2 ms exposure time [*Cummer et al.*, Geophys. Res. Lett., 33, L04104, 2006].

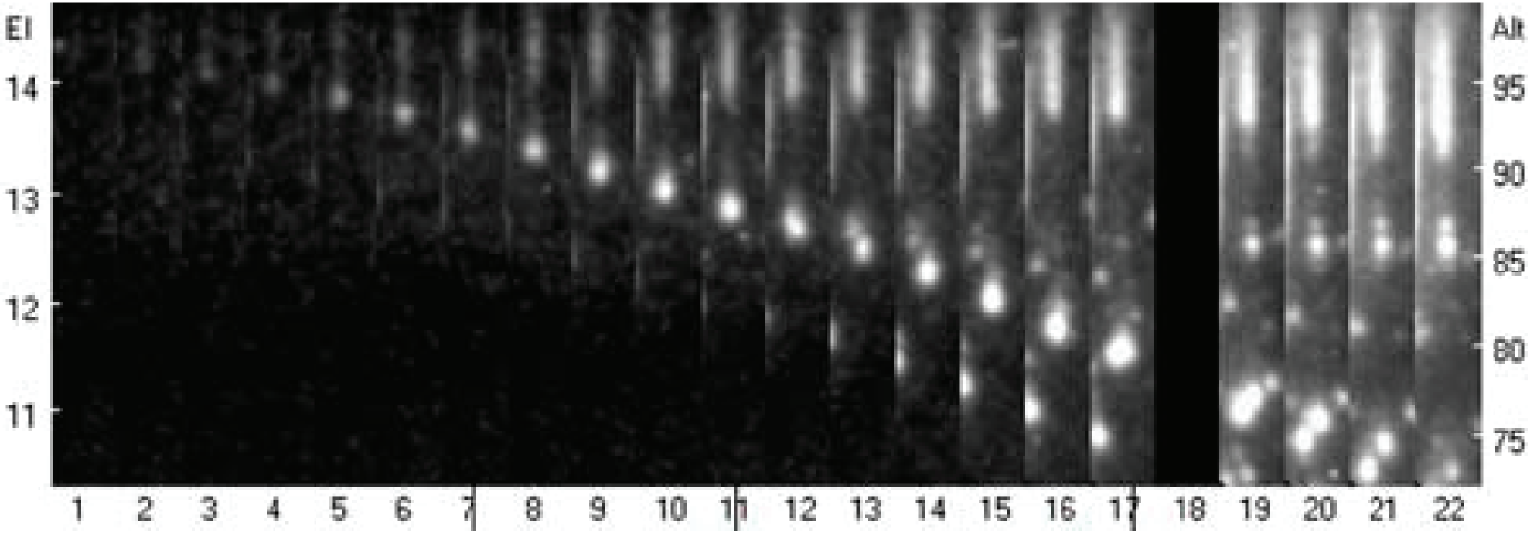


High Speed Imaging of Sprites

- High speed sprite images with $\sim$0.2 ms exposure time [*Cummer et al.*, Geophys. Res. Lett., 33, L04104, 2006].

High Speed Imaging of Sprite Streamers

- Sprite images recorded with 50 μs exposure time [*McHarg et al.*, Geophys. Res. Lett., 34, L06804, 2007; *Stenbaek-Nielsen et al.*, Geophys. Res. Lett., 34, L11105, 2007].



- General Morphology
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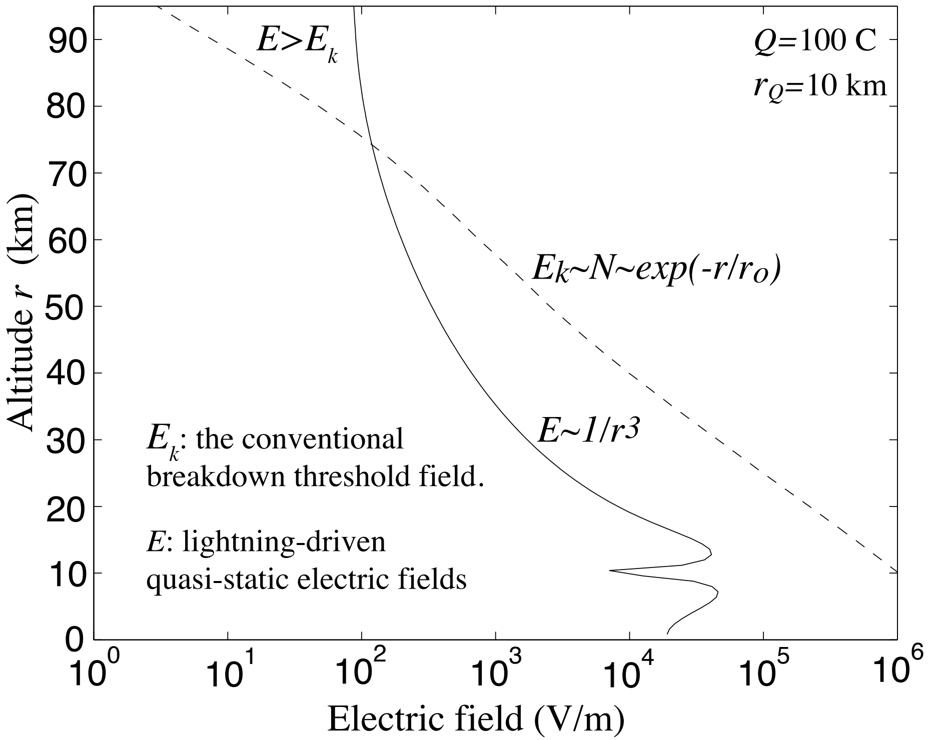
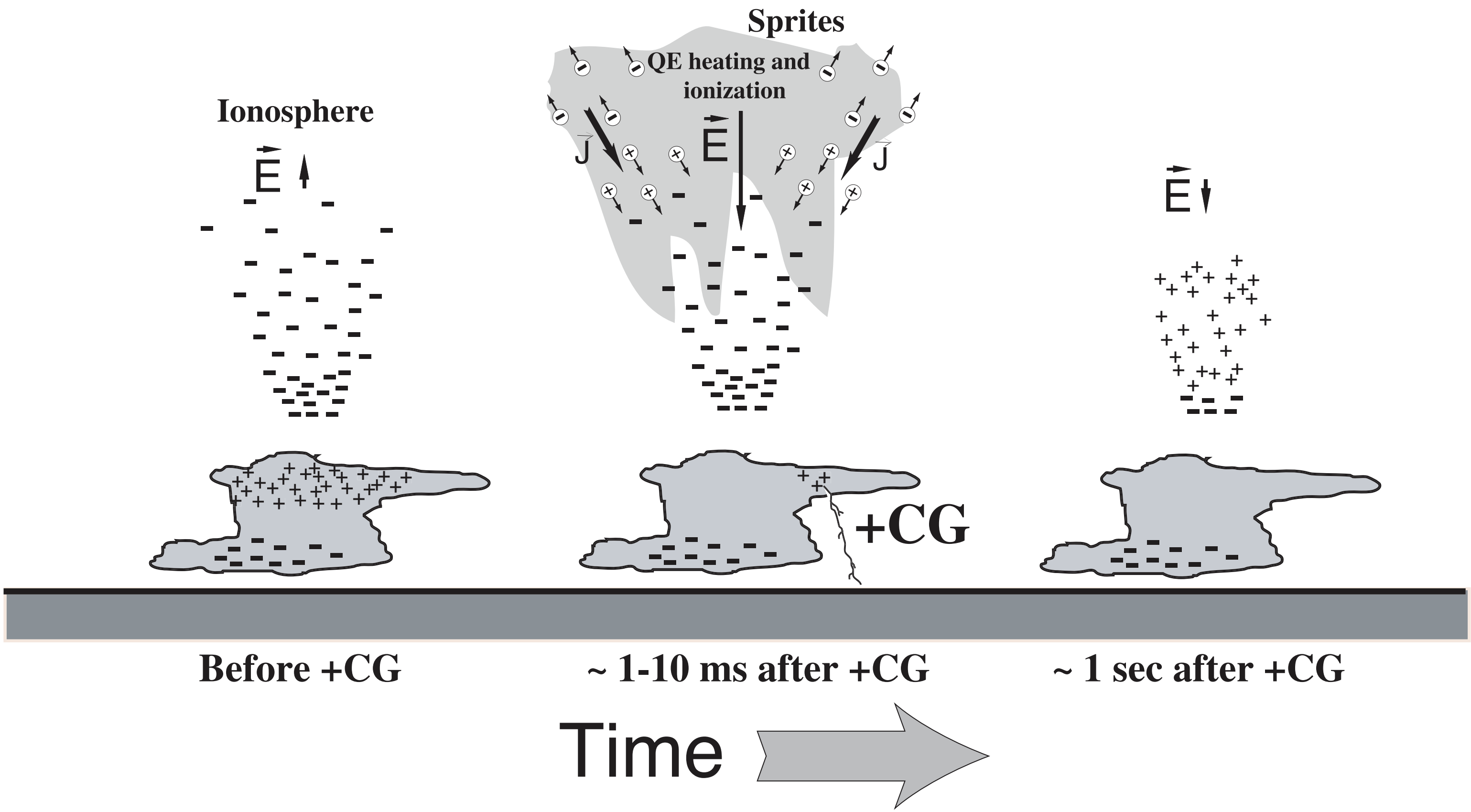
Physical Mechanism of Sprites - Wilson's Idea

"While the electric force due to the thundercloud falls off rapidly as *r* increase, the electric force required to cause sparking (which for a given composition of the air is proportional to its density) falls off still more rapidly. Thus, if the electric moment of a cloud is not too small, there will be a height above which the electric force due to the cloud exceeds the sparking limit."

C.T.R. Wilson, Proc. Phys. Soc. Lond., Vol. 37, P. 32D, 1925



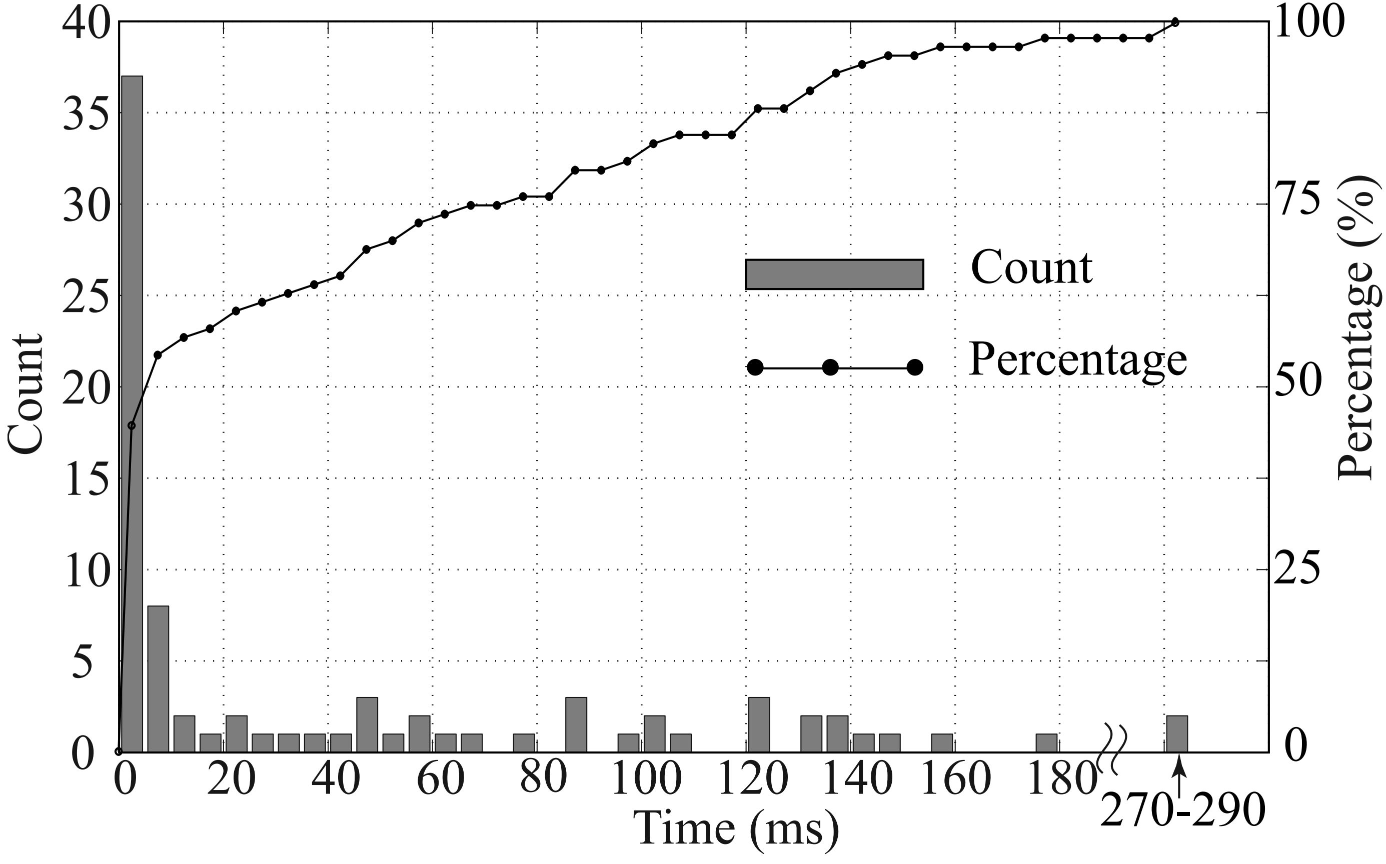
Physical Mechanism of Sprites



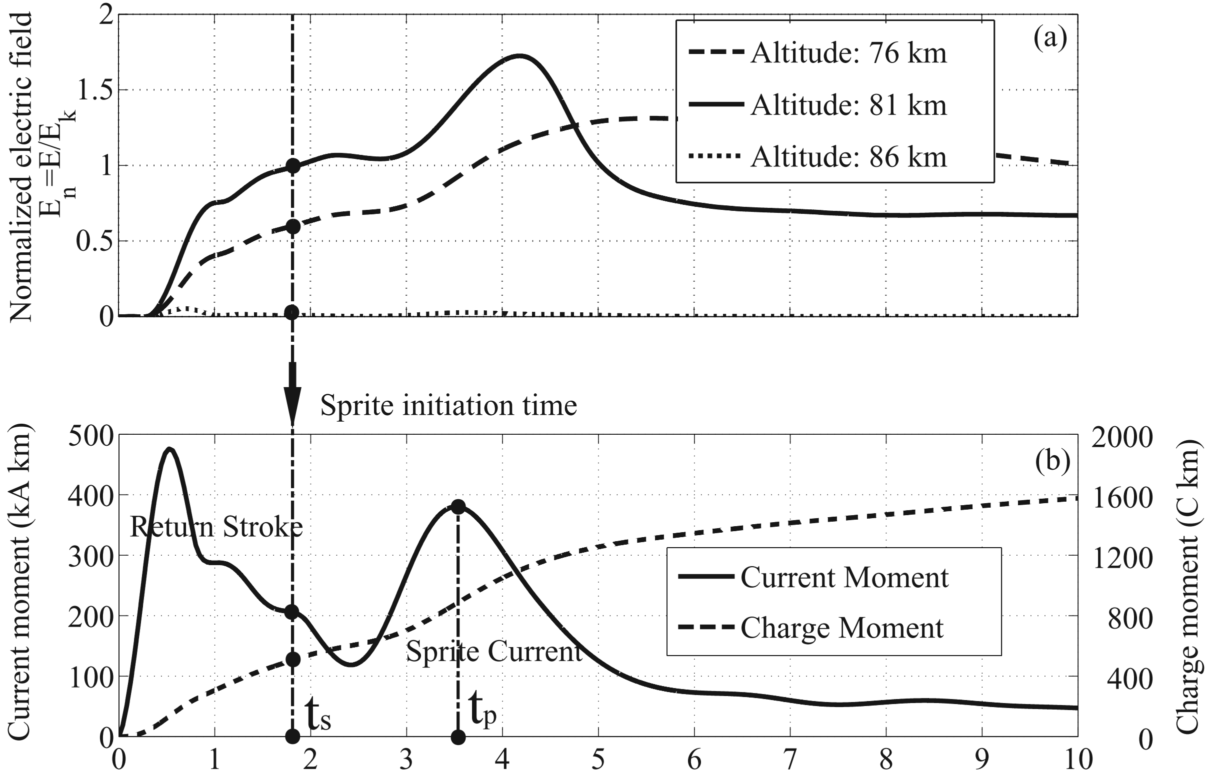
- Strong quasistatic electric field may briefly exist in the lower ionosphere following cloud-to-ground lightning [*Pasko et al.*, J. Geophys. Res., 102, 4529, 1997].

Delay Between Sprite Initiation and Parent Lightning Return Stroke

- Delays of 83 sprite events observed at Yucca Ridge, Colorado in the summer of 2005 [*Li et al.*, 2008].

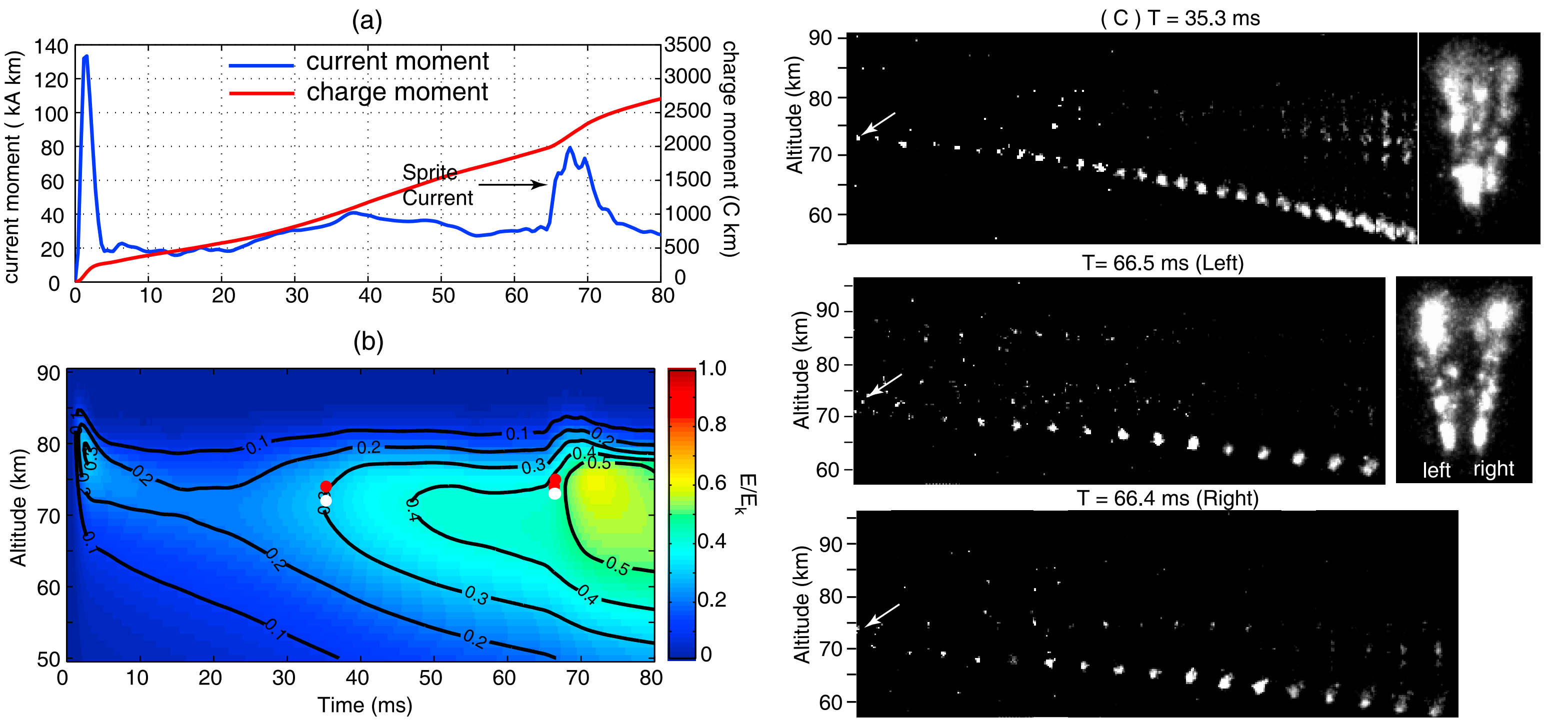


- The measurement-inferred mesospheric electric field agrees within 20% with the threshold electric field for conventional breakdown [*Hu et al.*, 2007].



Long-Delayed Sprites

- The normalized lightning quasistatic electric field at sprite initiation varies from 0.2-0.6 E_k [*Li et al.*, 2008; *Gamerota et al.*, 2011].



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Large Scale Sprite Modeling [*Liu*, 2012]

- Drift-diffusion equations coupled with Poisson's equation:

$$\frac{\partial n_i}{\partial t} + \nabla \cdot \vec{J}_i = S_i - L_i,$$
$$\nabla^2 \phi = -\frac{\rho}{\varepsilon_0},$$

where

n_i - the density of the ith charged species,

$\vec{J}_i$ - the flux density,

S_i - source,

L_i - loss,

ϕ - electric potential. $\vec{E} = -\nabla\phi$.

- The ion chemistry is a modified version of the model from [*Lehtinen and Inan*, 2007].
- Model species

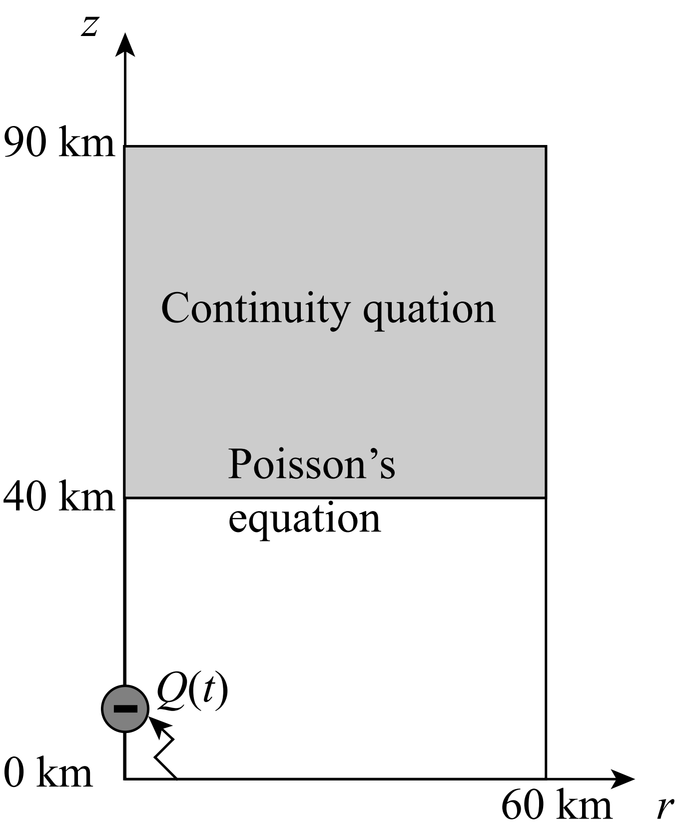
Neutral Species
Q M M_x M_{ac}

Charged Species
e O^- M^- M_x^- M^+ M_x^+

- Except the detachment process, O^- ions are included in a similar manner as other light negative ions.

Reaction No.	Reaction	Rate Constant
Cosmic ray background		
R1	$Q + M \rightarrow e + M^+ + Q$	1e-25
Electron impact reaction		
R2	$e + M \rightarrow e + e + M^+$	$f(E/N)$
R3	$e + O_2(M) \rightarrow O^- + O(M_{ac})$	$f(E/N)$
R4	$e + M + M \rightarrow M^- + M$	$f(E/N)$
Recombination		
R5	$e + M^+ \rightarrow M_{ac} + M_{ac}$	3e-13
R6	$e + M_x^+ \rightarrow M + M$	1e-12
R7	$M^- + M^+ \rightarrow M + M$	5e-13
R8	$M^- + M_x^+ \rightarrow M + M_x$	5e-13
R9	$O^- + M^+ \rightarrow O(M_{ac}) + M$	5e-13
R10	$O^- + M_x^+ \rightarrow O(M_{ac}) + M_x$	5e-13
R11	$M_x^- + M^+ \rightarrow M_x + M$	5e-13
R12	$M_x^- + M_x^+ \rightarrow M_x + M_x$	5e-13
R13	$M^- + M^+ + M \rightarrow M + M + M$	5e-37
R14	$M^- + M_x^+ + M \rightarrow M + M_x + M$	5e-37
R15	$O^- + M^+ + M \rightarrow O(M_{ac}) + M + M$	5e-37
R16	$O^- + M_x^+ + M \rightarrow O(M_{ac}) + M_x + M$	5e-37
R17	$M_x^- + M^+ + M \rightarrow M_x + M + M$	5e-37
R18	$M_x^- + M_x^+ + M \rightarrow M_x + M_x + M$	5e-37
Ion conversion		
R19	$M^+ + M + M \rightarrow M_x^+ + M$	2e-42
R20	$M_x^+ + M \rightarrow M^+ + M + M$	2e-22
R21	$M_x^+ + M_{ac} \rightarrow M^+ + M$	1e-16
R22	$M^- + M + M \rightarrow M_x^- + M$	1e-43
R23	$O^- + M + M \rightarrow M_x^- + O(M_{ac})$	3e-43
R24	$M_x^- + M_{ac} \rightarrow M^- + M$	2e-16
Electron detachment		
R25	$M^- + M \rightarrow e + M + M$	2e-29
R26	$M^- + M_{ac} \rightarrow e + M + M_{ac}$	2.5e-16
R27	$O^- + M \rightarrow e + M_x$	$f(E/N)$
R28	$O^- + M \rightarrow e + M_x$	1e-21
R29	$O^- + M_{ac} \rightarrow e + M$	4e-16

Simulation Setup



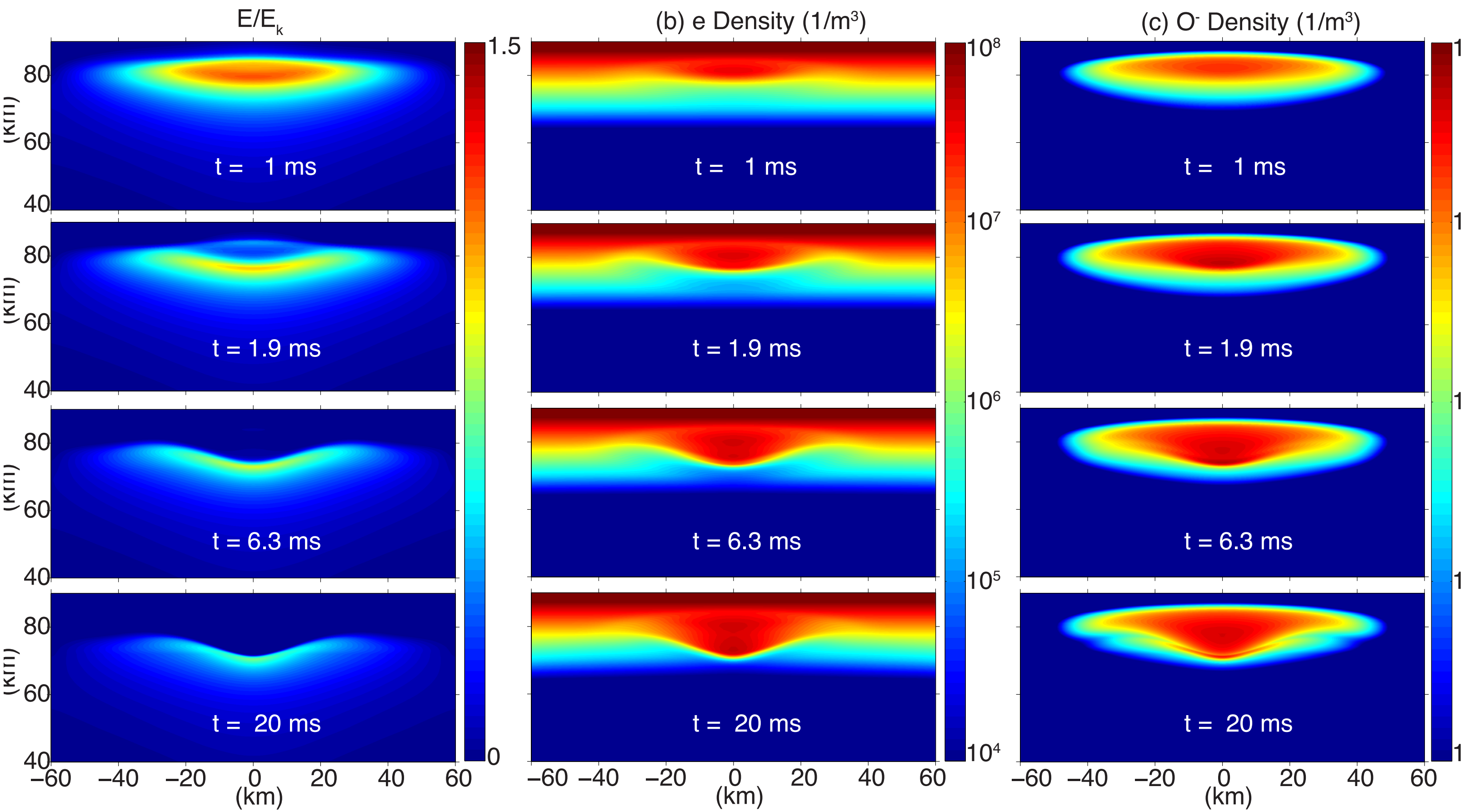
- $Q(t)$ has the following form [*Pasko et al.*, 1997]:

$$
\begin{aligned}
Q(t) &= Q_0 \frac{\tanh(t/\tau_f)}{\tanh(1)}, \ 0 \le t < \tau_f, \\
Q(t) &= Q_0, \qquad\qquad\qquad t \ge \tau_f
\end{aligned}
$$

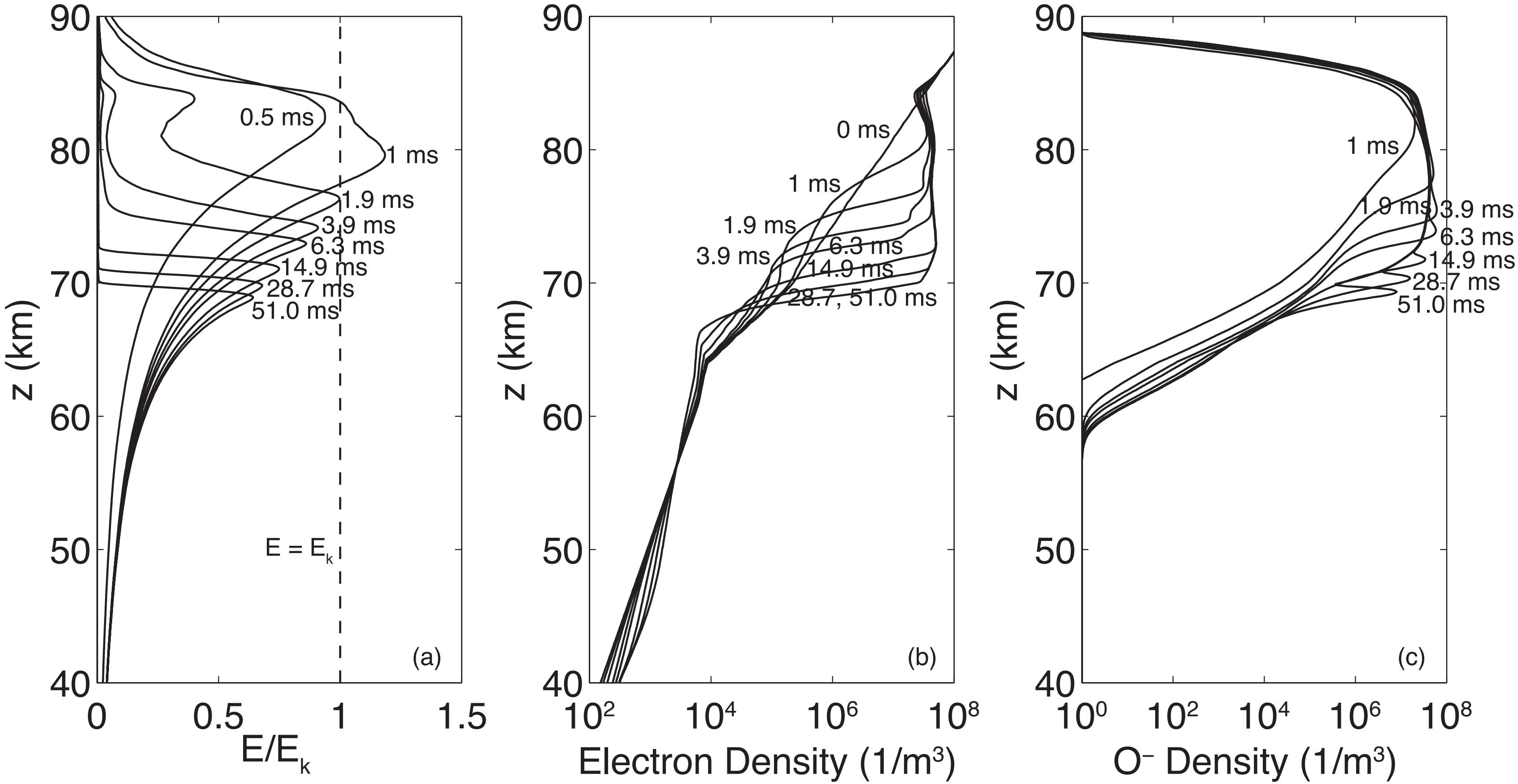
- $\tau_f = 1$ ms.

Sprite Halo Caused by +CG

- Sprite halo by +CG with 600 C km charge moment change.



Altitude Profiles of a Positive Sprite Halo [*Liu*, 2012]



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Streamer Model Equations

- Drift-diffusion equations coupled with Poisson's equation [*Liu and Pasko*, J. Geophys. Res., 109, A04301, 2004]:

$$\begin{aligned}
\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}_e) - D_e \nabla^2 n_e &= (\nu_i - \nu_{a2} - \nu_{a3}) n_e - \beta_{ep} n_e n_p + S_{ph}, \\
\frac{\partial n_p}{\partial t} &= \nu_i n_e - \beta_{ep} n_e n_p - \beta_{np} n_n n_p + S_{ph}, \\
\frac{\partial n_n}{\partial t} &= (\nu_{a2} + \nu_{a3}) n_e - \beta_{np} n_n n_p, \\
\nabla^2 \phi &= -\frac{e}{\varepsilon_0}(n_p - n_e - n_n),
\end{aligned}$$

where

n_e, n_p, n_n – the density of electrons and ions,

v_e – drift velocity,

D_e – diffusion coefficient,

ν_i – electron impact ionization frequency,

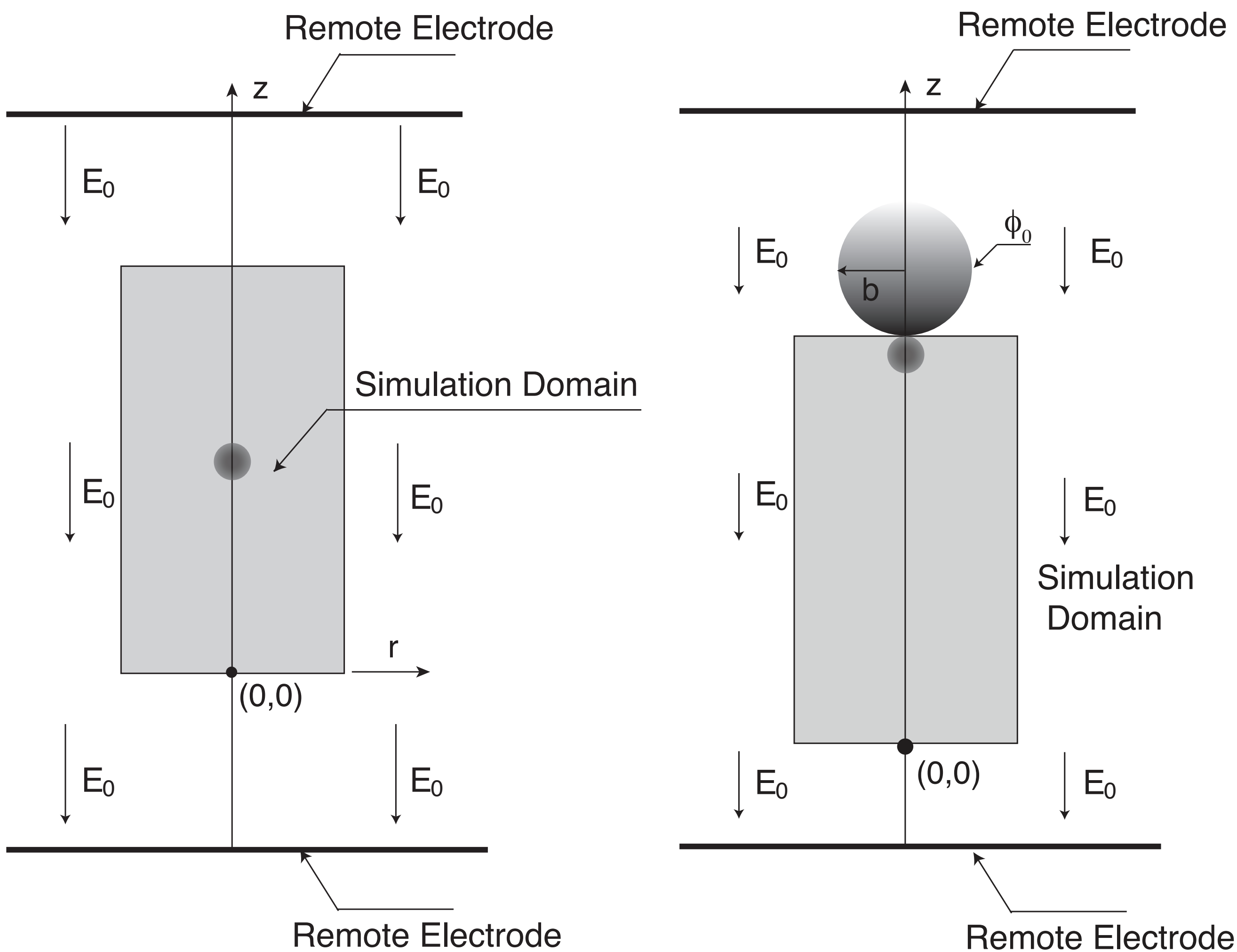
ν_{a2}, ν_{a3} – two-body and three-body attachment frequencies,

β_{ep}, β_{np} – recombination coefficients,

S_{ph} – photoionization rate,

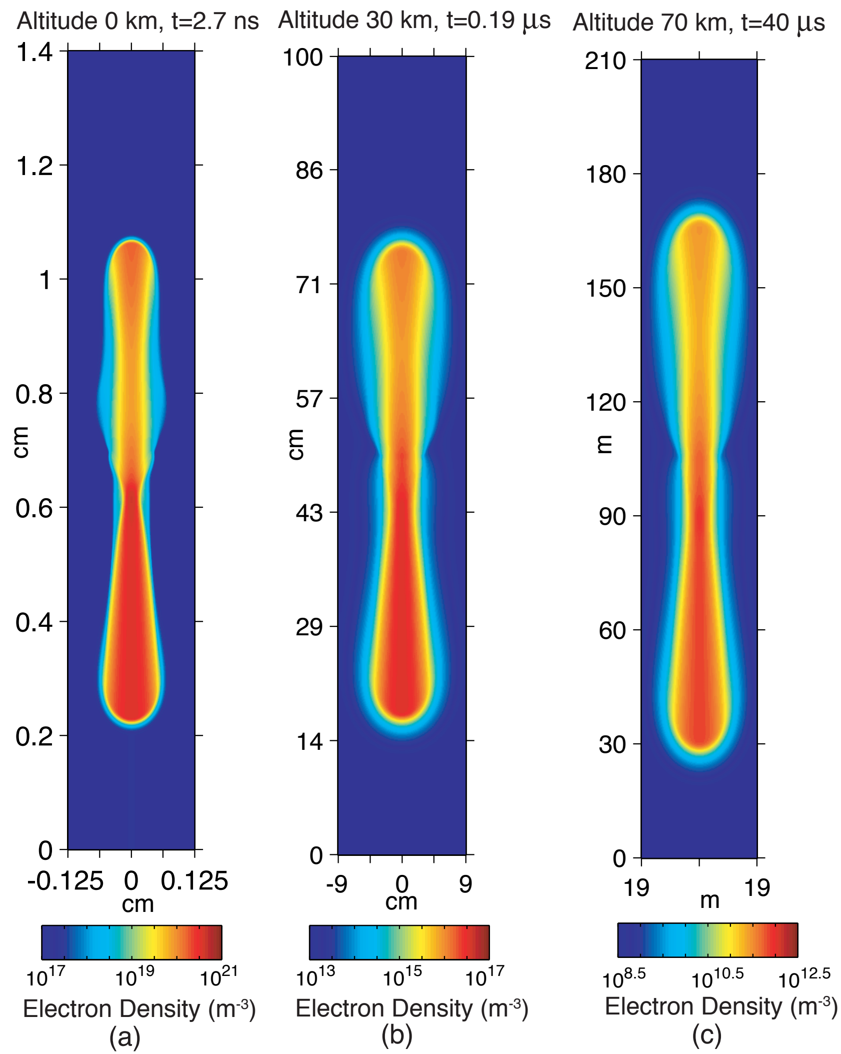
ϕ – electrostatic potential.

Simulation Domain for Sprite Streamers

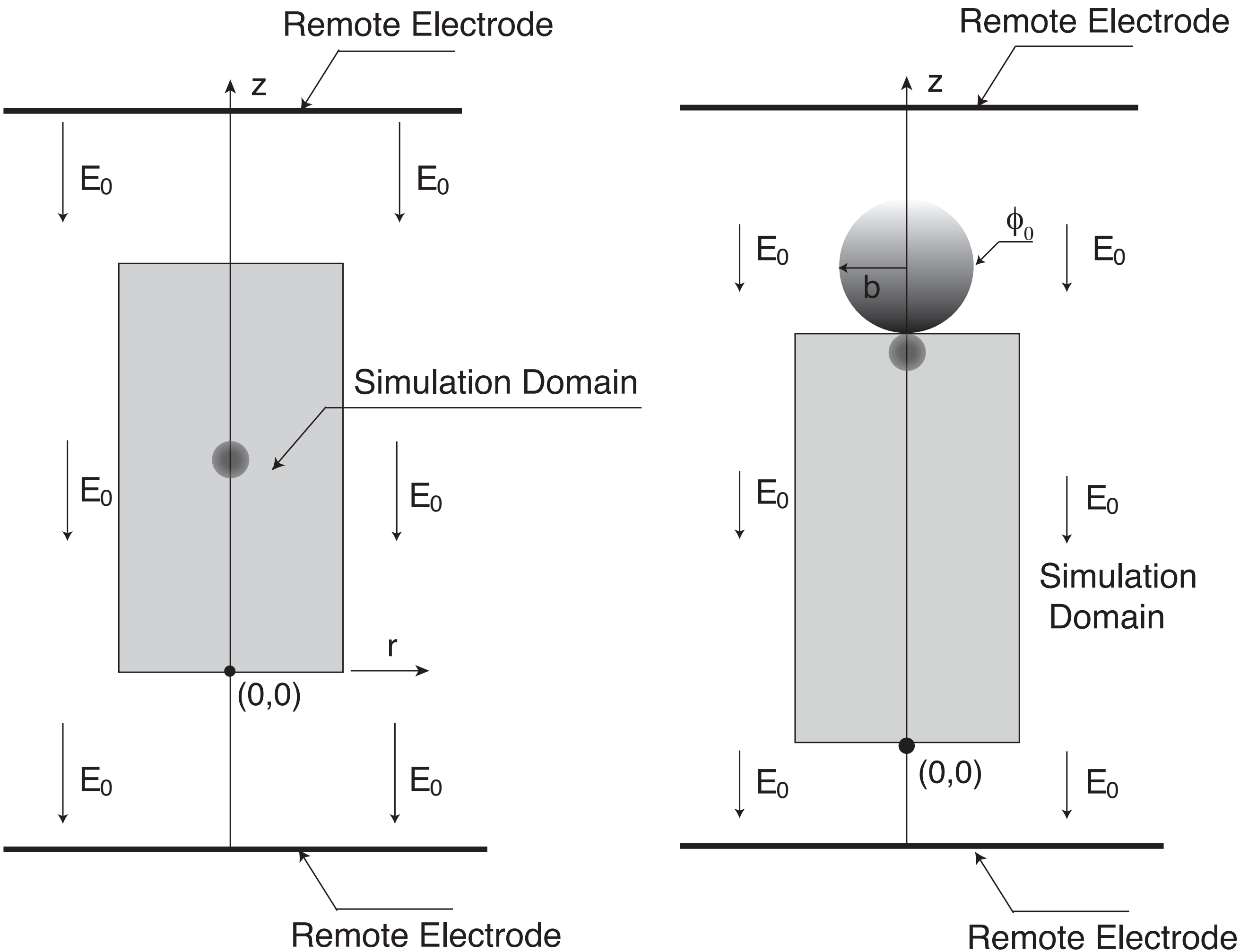


Double Headed Streamers

- Streamers developing in $E_0 = 1.5E_k$ at three altitudes: 0, 30, and 70 km [*Liu and Pasko*, J. Geophys. Res., 109, A04301, 2004].
- Each streamer consists of a downward propagating positive streamer head and upward propagating negative streamer head.
- Streamer heads expand during propagation.
- The three streamers look very similar but have very different temporal and spatial scales - similarity laws for streamer discharges at different pressures.

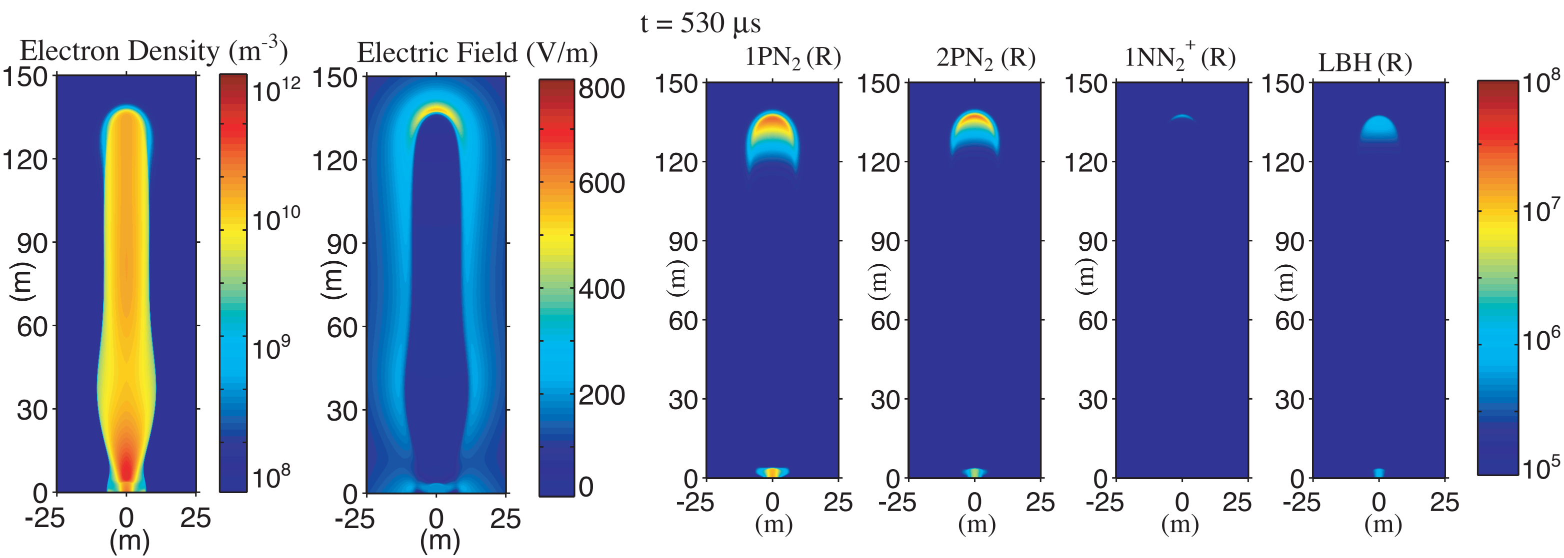


Simulation Domain for Sprite Streamers



Sprite Streamer Developing in Propagation Threshold Field

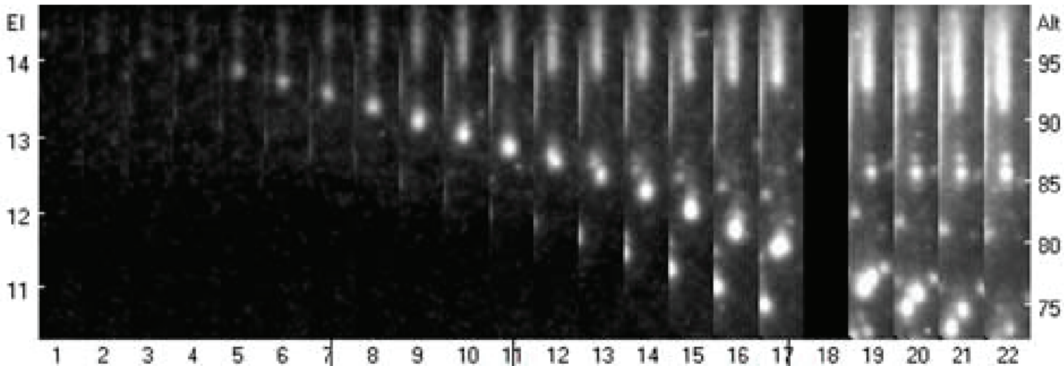
- Development of a positive sprite streamer in $E_0 = 0.16E_k$ [*Liu and Pasko*, Geophys. Res. Lett., 32, L05104, 2005].

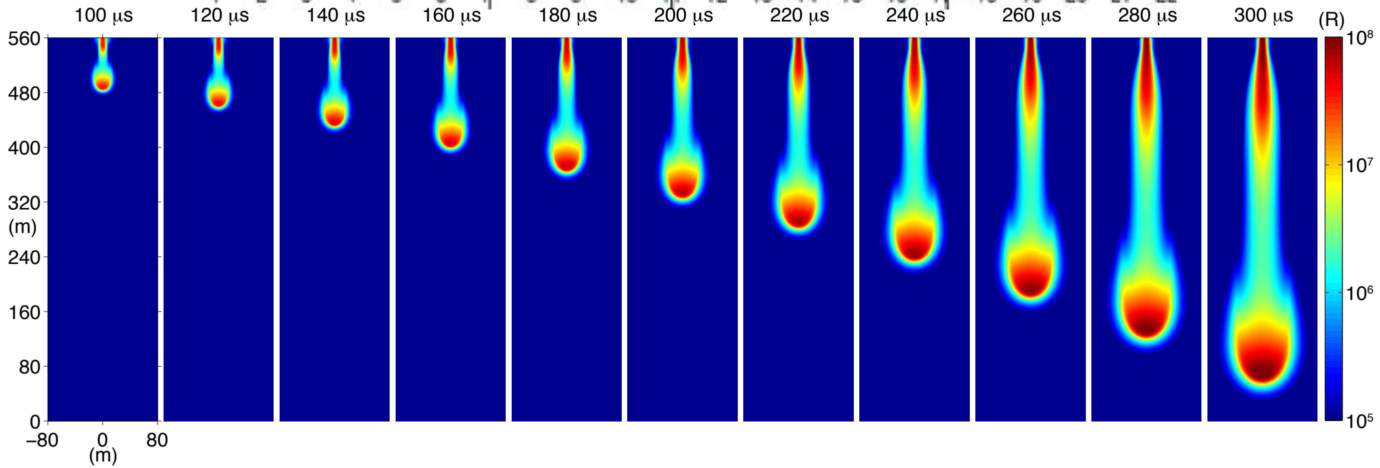


- There is no clear expansion of streamer channel.
- Emissions are localized in the streamer head.

Comparison Between Sprite Streamer Modeling and Observations

- High speed images of sprite streamers [*McHarg et al.*, 2007; *Stenbaek-Nielsen et al.*, 2007].

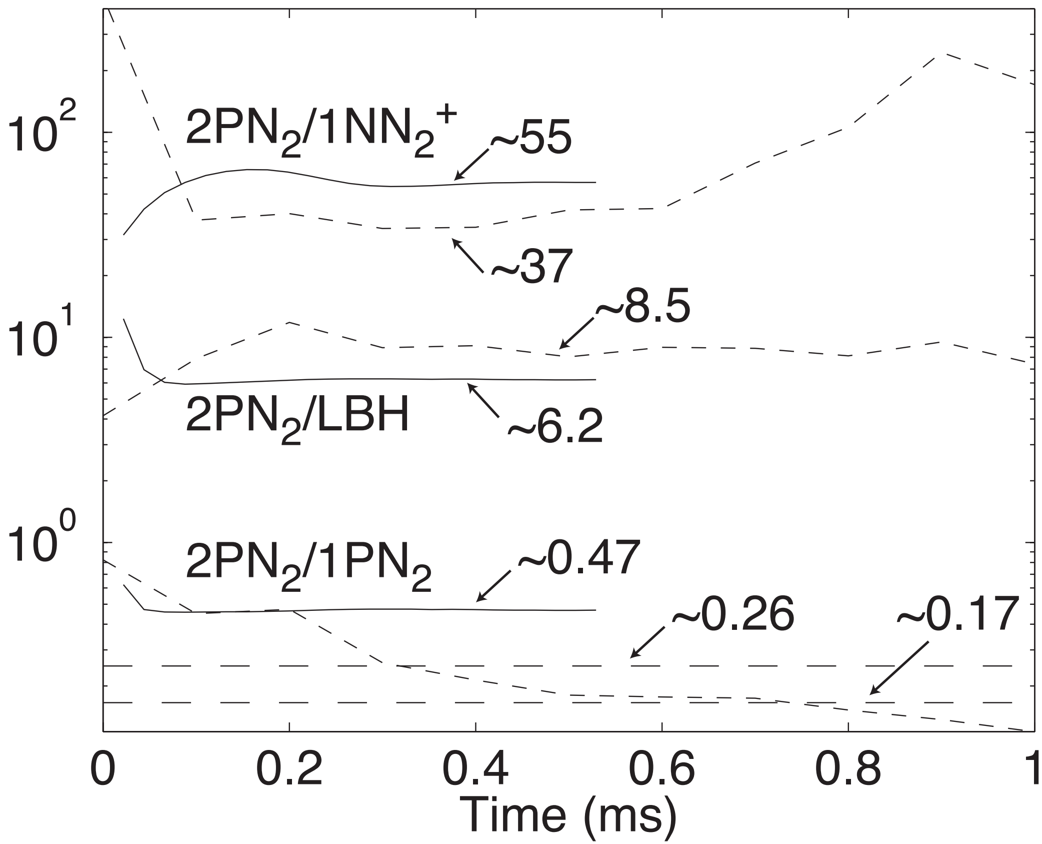




- The model sprite streamer at 75 km altitude [*Liu et al.*, 2009a].

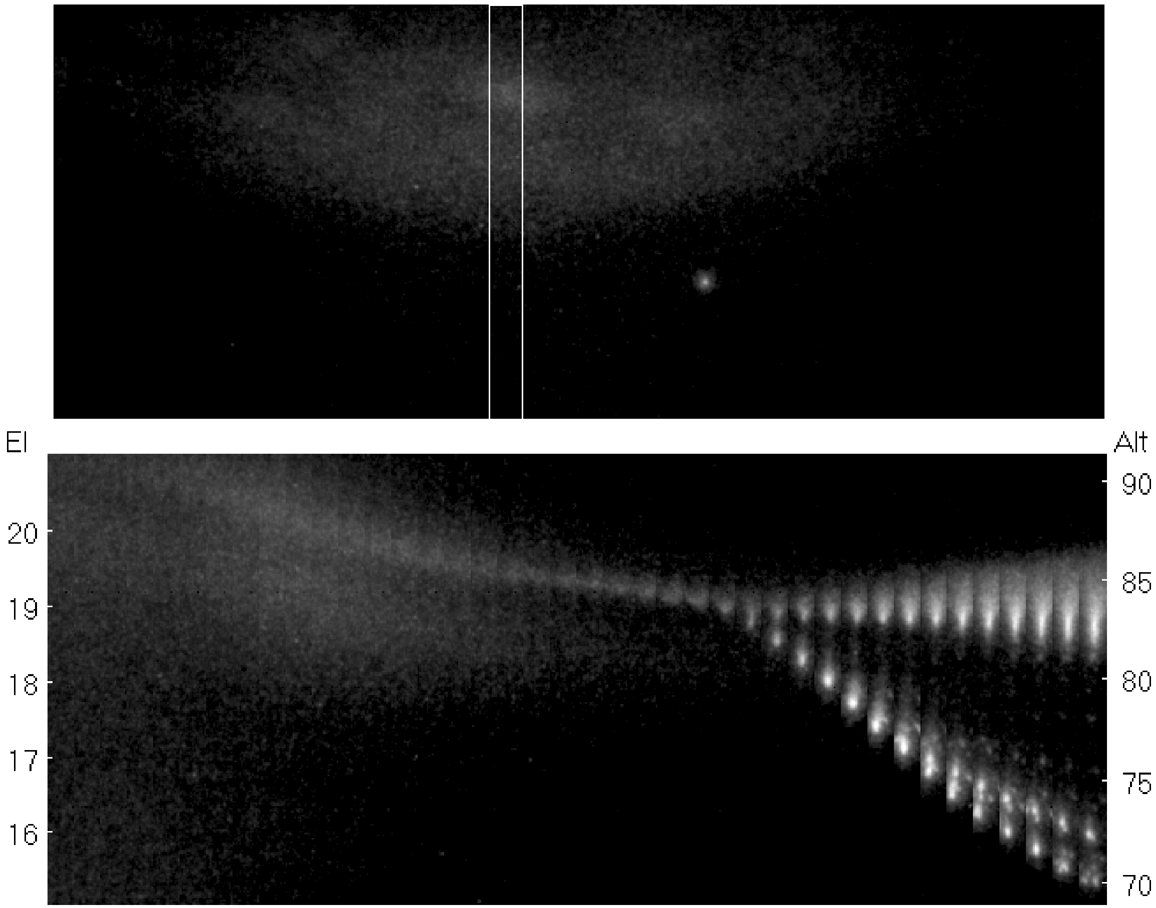
Comparison Between Streamer Modeling Results with ISUAL Measurements

- The intensity ratio between 2PN_2 and other emission band systems [*Liu et al.*, 2006, 2009b].



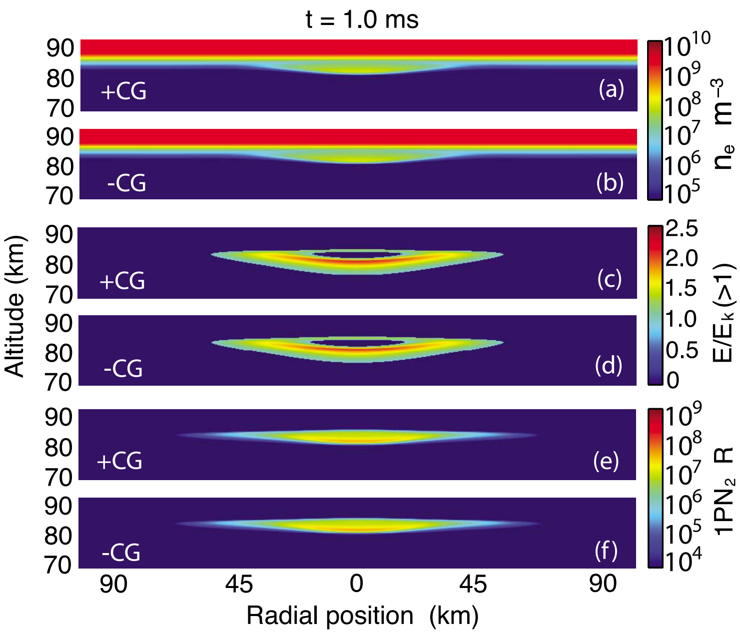
Sprite Streamer Initiation from Halo Structures

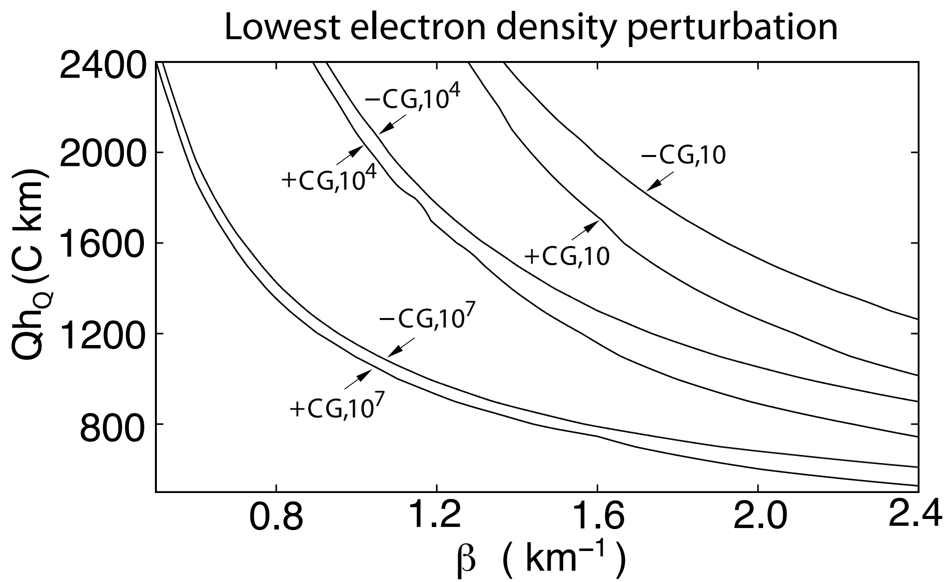
- Sprite streamer initiation (20 μs exposure) from structures appearing at the bottom of a halo [*Stenbaek-Nielsen et al.*, 2013].



Important Parameters Determining Sprite Streamer Initiation

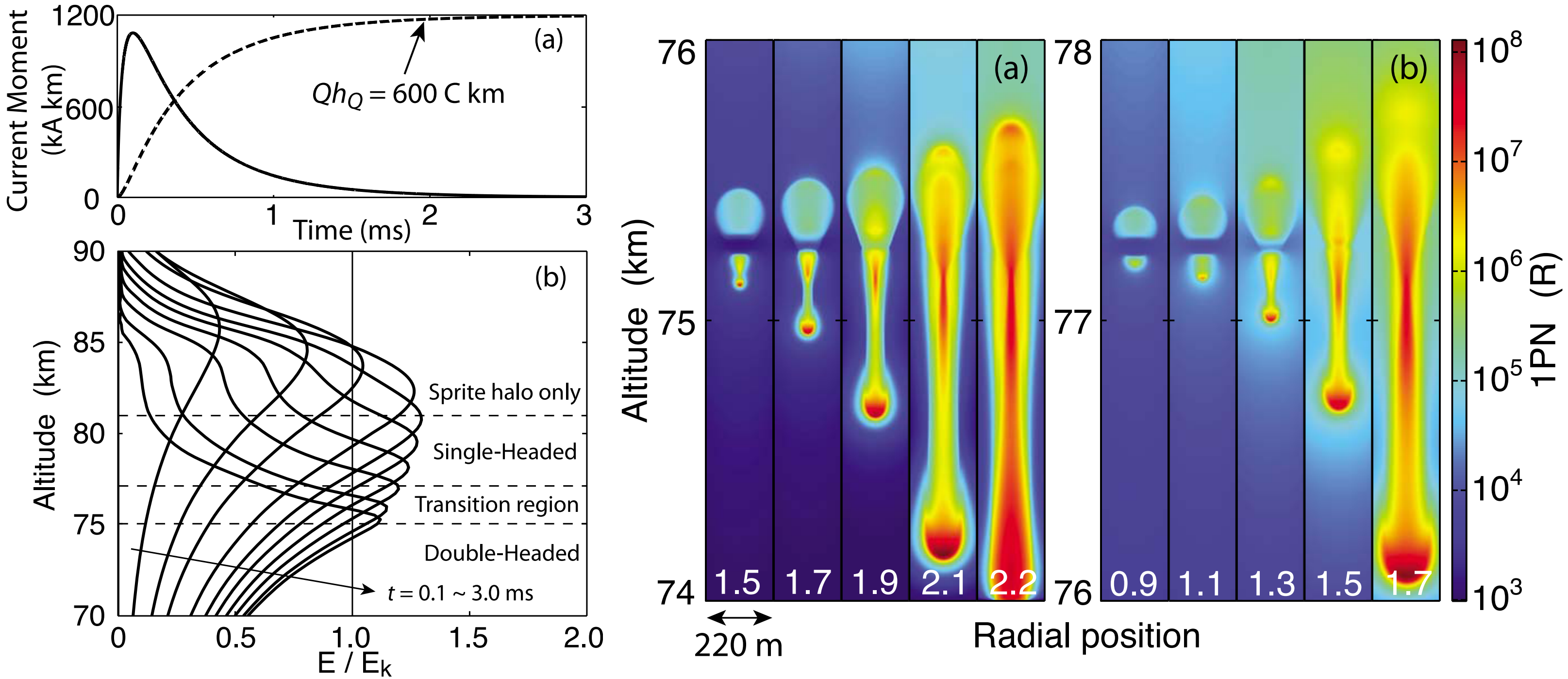
- Important parameters determining sprite streamer initiation include charge moment change, ionospheric inhomogeneity magnitude, and the sharpness of ambient density profile [*Qin et al.*, 2011].





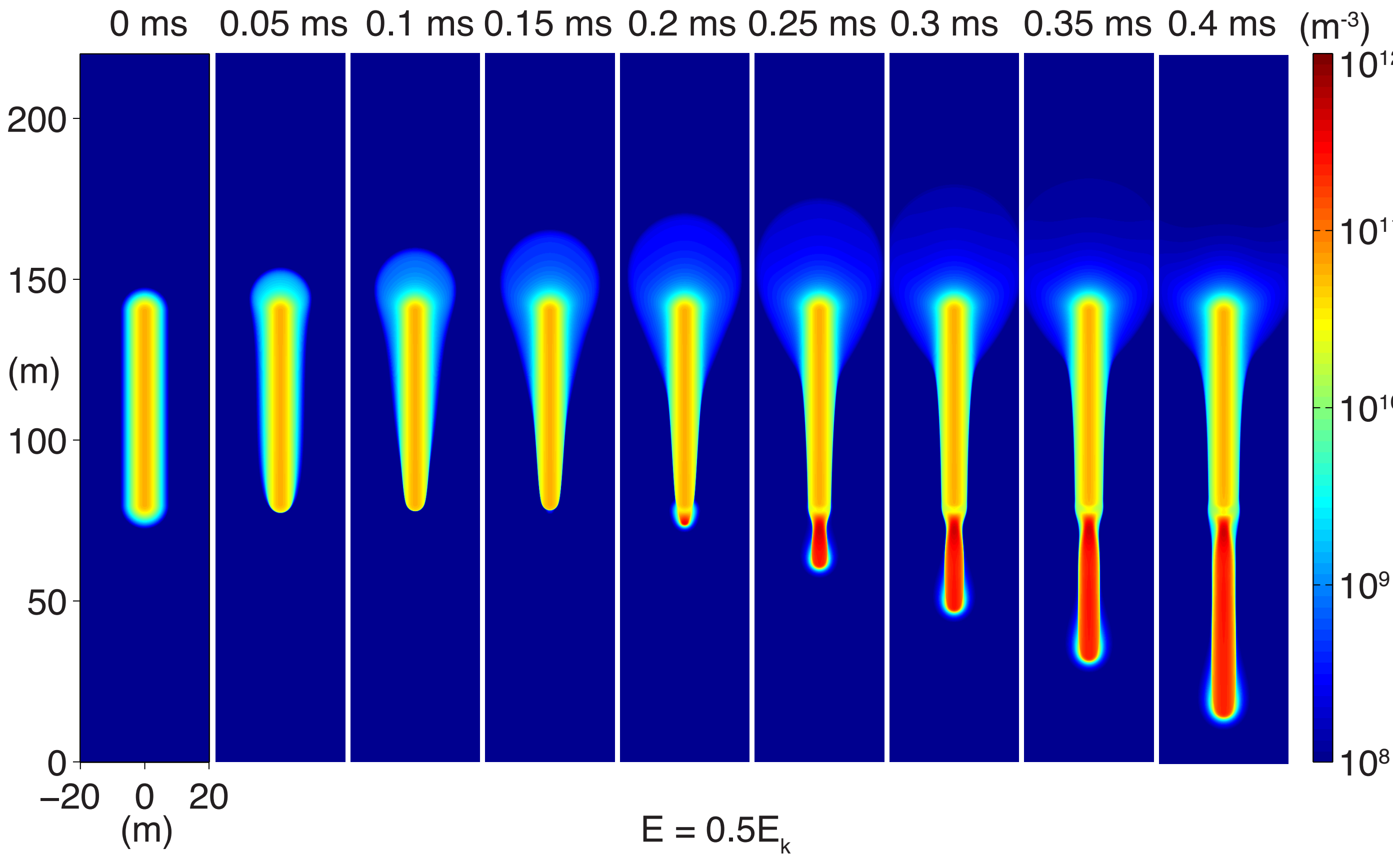
Single or Double-Headed Streamers

- If lightning field $> E_k$, inhomogeneities in halos will lead to single-headed streamers and those at and below the lower edge of the sprite halo will lead to double-headed streamers [*Qin et al.*, 2012].



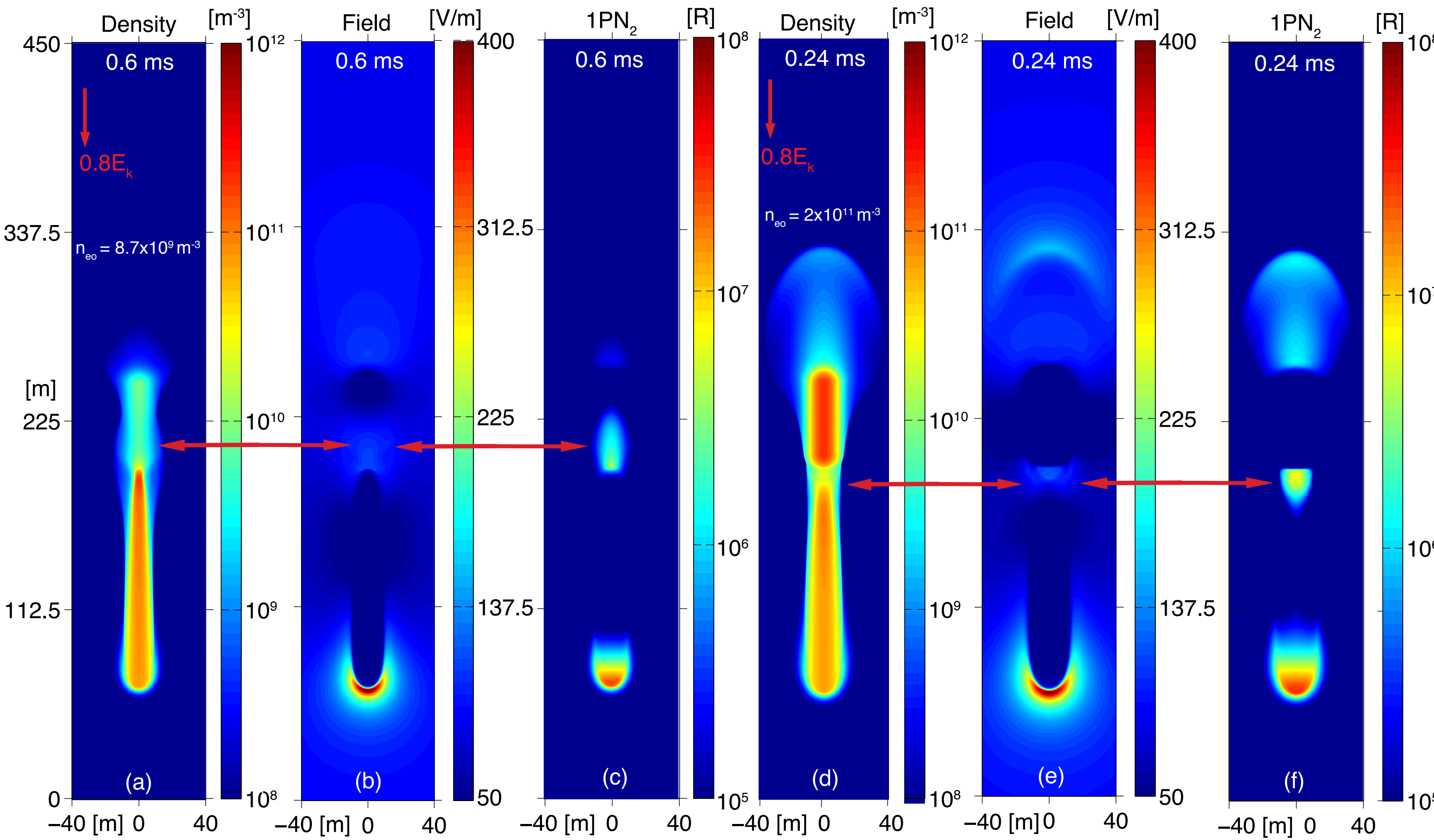
Streamer Formation from Ionospheric Inhomogeneities

- Initiation of positive streamers in a subbreakdown field [*Liu et al.*, 2012].



- This offers an explanation to observation of sprite initiation below E_k.

Brightening of Streamer Initiation Point



- Brightening of the streamer origin agrees with observations [*Kosar et al.*, 2012].

Problems in Theory of Sprite and Streamer Discharges

Categories of problems in the sprite theory:

- Initiation
- Structures and dynamics
- Optical emission spectrum
- Infrasound signatures
- Chemical effects
- Effects on the propagation of electromagnetic waves

Categories of problems in the theory of streamer discharges:

- Branching
- Chemical effects
- Heating effects
- Interactions between streamers