Air-density-dependent model for analysis of air heating associated with streamers, leaders, and transient luminous events

Transient Luminous Events and TGFs
Lightning Effects on the Upper Atmosphere

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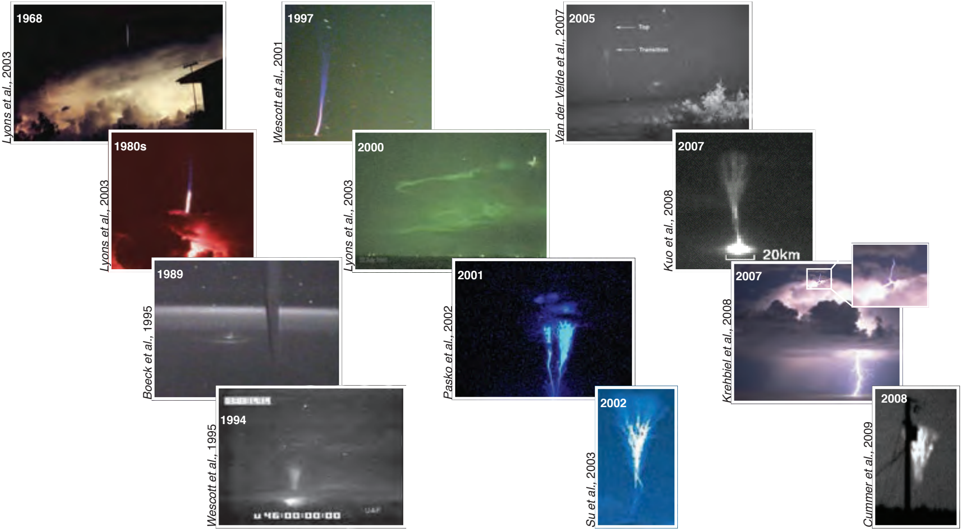
Observations of Upward Discharges



Streamer-to-Leader Transition in Jets

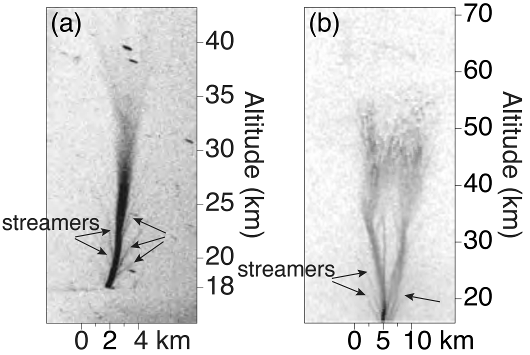
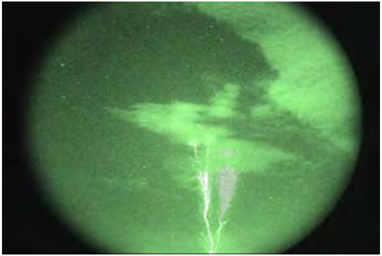


Figure: (a) A black and white image of a 2-min time exposure of a blue jet [Wescott et al., 2001]. (b) Processed image obtained by averaging of sequence of video fields from observations reported in Pasko et al. [2002].

▷ Streamer structure of jets was first suggested by Petrov and Petrova [1999]



[Pasko et al., 2002]

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Mechanisms of Conductivity Increase [Naidis, 1999]

Thermal Mechanism

1. Heated gas expands
2. Gas number density is lowered
3. Ratio E/N increases
4. Ionization rate grows
5. Conductivity increases

Kinetic Mechanism

1. Active particles (radicals and excited molecules) accumulate
2. Detachment, electron impact ionization of radicals and associative ionization accelerate
3. Balance between rates of generation and loss of electrons changes
4. Conductivity increases

Depending on the regime, one mechanism dominates.

Model of Streamer-to-Spark Transition: 1-D Gas Dynamics Model

- 1-D axisymmetric model
- Vibrational-translational relaxation processes
- Fast heating of air in the streamer channel

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) &= 0 \\
\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) &= -\nabla p \\
\frac{\partial \varepsilon}{\partial t} + \nabla \cdot \{(\varepsilon + p)\, \vec{v}\} &= \eta_T Q_e + Q_i + Q_{VT} \\
\frac{\partial \varepsilon_v}{\partial t} + \nabla \cdot (\varepsilon_v \vec{v}) &= \eta_V Q_e - Q_{VT}
\end{aligned}
$$

- Q_e, Q_i, and Q_{VT} depend on n_O, $n_{O_2^+}$, $n_{O_4^+}$, $n_{O_2^+N_2}$, n_{O^-},$n_{O_2^-}$, $n_{O_3^-}$, and n_e derived from the kinetics model

Model of Streamer-to-Spark Transition: 0-D Chemical Kinetics Scheme

- 15 components:
  - Neutral particles: N_2, O_2, O, N, NO, $N_2(A^3\Sigma_u^+)$, $N_2(B^3\Pi_g)$, $N_2(C^3\Pi_u)$, $N_2(a'^1\Sigma_u^-)$, $O_2(a^1\Delta_g)$
  - Positive ions: O_2^+, O_4^+, $O_2^+N_2$
  - Negative ions: O^-, O_2^-, O_3^-
  - Electrons: e
- Effects of gains in electron energy in collisions with vibrationally excited nitrogen molecules on the rate constants of ionization and dissociative attachment processes [e.g., Benilov and Naidis, 2003]
- Self-quenching of $N_2(A^3\Sigma_u^+)$
- Associative ionization of $N_2(A^3\Sigma_u^+)$ and $N_2(a'^1\Sigma_u^-)$
- General balance equation:

$$\frac{dn_e}{dt} = \left(F_{ion} + F_{step} + F_d - F_{a_2} - F_{a_3} - F_{rec}\right) n_e$$

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Comparison with Experimental Results

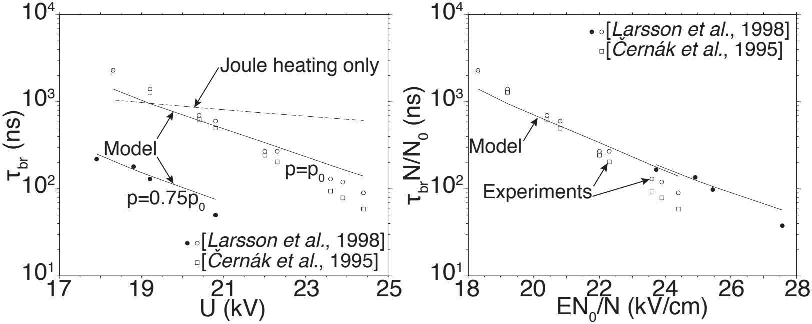

Figure: (left) Experimental and model streamer-to-spark transition times for various applied voltages. The solid lines represent the transition times under normal pressure (p=10^5 Pa) and reduced pressure (p=0.75×10^5 Pa). (right) Same model and experimental data as in left panel but using reduced values of the applied field (EN_0/N) and of the transition times ($\tau_{\rm br}N/N_0$).

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Streamer-to-Spark Transition at 0 and 70 km Altitudes

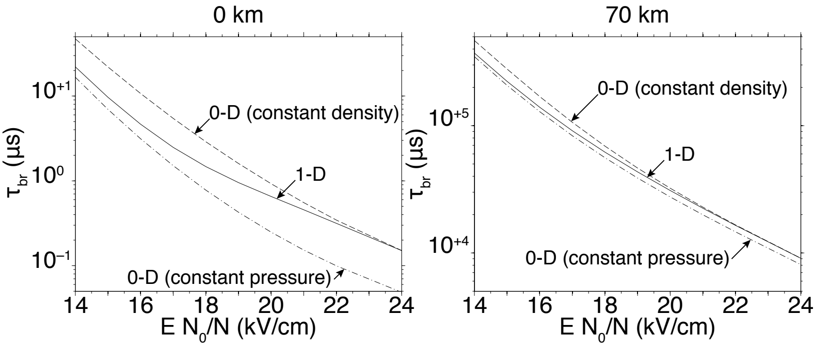

Figure: Streamer-to-spark transition time at 0 km (left) and 70 km (right) altitudes.

Streamer-to-Spark Transition at 0 and 70 km Altitudes

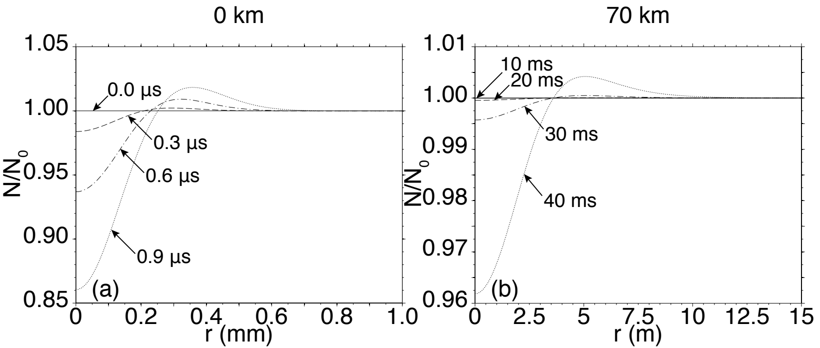

Figure: Distribution of the reduced gas density on the radial coordinate for EN_0/N = 19 kV/cm at 0 km at t=0, 0.3, 0.6, and 0.9 μs (left), and at 70 km at t=10, 20, 30, and 40 ms (right).

Streamer-to-Spark Transition at 0 km Altitude

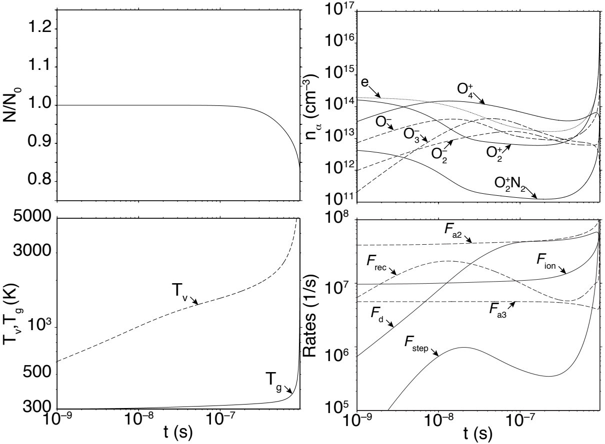

Figure: Streamer-to-spark dynamics at sea level for EN_0/N = 19 kV/cm.

The major cause of spark formation:

- Heated gas expansion
- Accumulation of oxygen atoms and other active species [Naidis, 1999]
- Increase with time in the electron detachment rate
- Existence of two- and three-body processes

Streamer-to-Spark Transition at 70 km Altitude

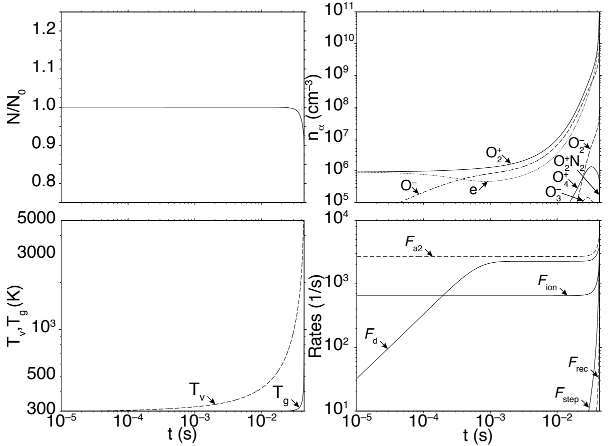

Figure: Streamer-to-spark dynamics at 70 km for EN_0/N = 19 kV/cm.

The major cause of spark formation:

- Gas expansion negligible
- Accumulation of oxygen atoms and other active species [Naidis, 1999]
- Increase with time in the electron detachment rate
- Disappearance of three-body processes

Scaling with Air Density

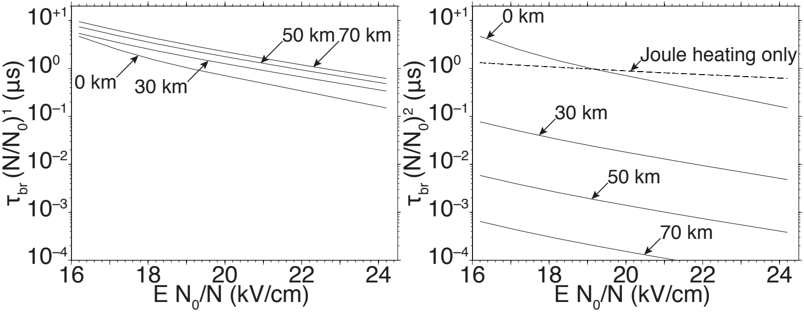

Figure: Scaling of the breakdown times as a function of the neutral density for various applied electric fields and altitudes (0, 30, 50, and 70 km).

$\tau_{\text{br}} \propto 1/N^{-1.11}$

- faster than the timescale of Joule heating ($\propto N^{-2}$)
- slower than that of the vibrational–translational relaxation ($\propto N^{-1}$)

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Principal Contributions

The principal results and contributions, which follow from the studies presented in this work, can be summarized as follows:

1. A 1-D axisymmetric air density dependent model of streamer-to-spark transition is introduced.
2. The streamer-to-spark transition model results are successfully compared to experimental data obtained by Černák et al. [1995] and Larsson et al. [1998] at ground and near ground pressures.
3. For a broad range of air densities (between altitudes 0 and 70 km) studied the streamer-to-spark transition time is demonstrated to scale with neutral density approximately as: $\tau_{\rm br} \propto 1/N$ therefore exhibiting a significant acceleration of the heating at low air densities in comparison with $1/N^2$ scaling predicted on the basis of simple similarity laws for Joule heating.

Acknowledgements

THANK YOU FOR YOUR ATTENTION
QUESTIONS?

This work is available online at:
`http://web.me.com/riousset/`

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