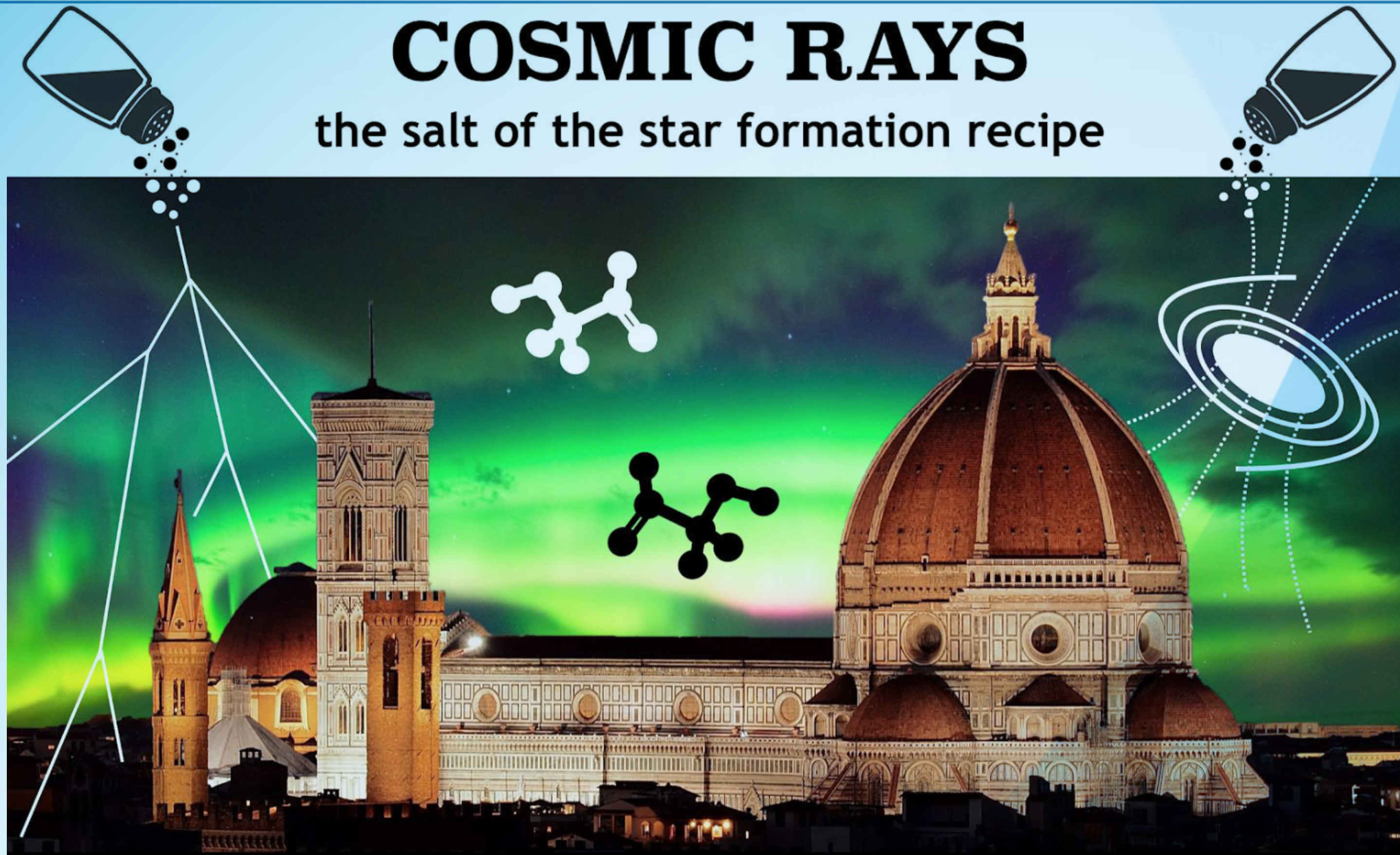


The simulation of stratospheric discharges sustained by the secondary electrons from cosmic rays

Vasily Kozhevnikov
Institute of High Current Electronics, Tomsk, Russian Federation
Vasily.Y.Kozhevnikov@ieee.org

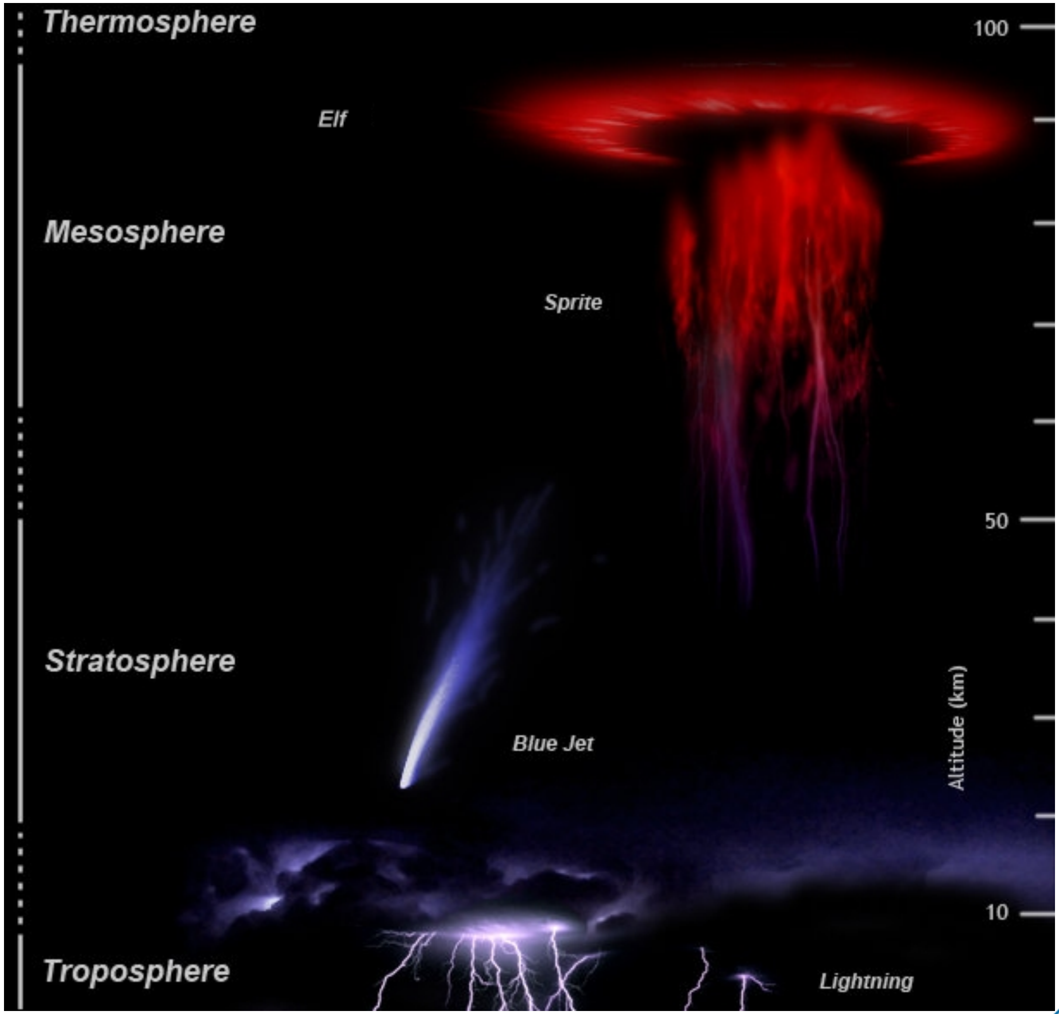
IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY
IHCE SB RAS
IEEE

Florence, 2018

Motivation

How to describe the initiation and the development of upper-atmospheric lightning (transient luminous events, TLE)?

- Typical electric field values (e.g. in stratosphere) are much less than breakdown values;
- In contrast to tropospheric lightning, TLE have a very wide range of visual manifestations (blue jets, blue starters, sprites, elfs, gigantic jets, etc.);



E.M. Wescott et al. // J. Geo. Res.: Space Phys. 106 (A10), 2001, pp. 21549-21554

Runaway breakdown* (RB) = TLE origin?

In atmospheric conditions runaway breakdown takes place at electric fields an order of magnitude weaker than those needed for normal breakdown in air, when following conditions are satisfied:

1) The value electric *E* field strength exceeds so-called "critical" value E_c

$$E \geq E_c \equiv \frac{4\pi e^3 Z N_n}{mc^2} a, \qquad E_c \approx 2.2 \frac{kV}{cm} \cdot \frac{P}{P_n} << E_{br} \approx 23 \frac{kV}{cm}$$

2) The spatial scale *L* of the electric field exceeds the length of the avalanche growth l_a

$$L \ ? \ l_a \equiv \frac{m^2 c^4}{2\pi N_n Z e^4} \frac{E_c}{E}, \qquad l_a \approx 50\, m \cdot \frac{E_c}{E} \cdot \frac{P_0}{P}$$

3) Fast seed electrons with energies above ε_c are present

$$\varepsilon \geq \varepsilon_c \equiv \frac{mc^2}{2} \cdot \frac{E_c}{E}, \qquad \varepsilon_c \approx 2.5 MeV \cdot \frac{E_c}{E}$$

*A.V. Gurevich, and K.P. Zybin // UFN, 44(11), pp.1119–1140 (2001)

Upper-atmospheric conditions for RB

1) "Critical" field value falls exponentially with the attitude $E_c \sim exp(-h)$ and the air conductivity above 20-30 km is high, so there is almost **no electric field** at 20-50 km attitudes.

However, the **positive lightning often violates** the electroneutrality condition providing the electric fields above critical value $E > E_c$

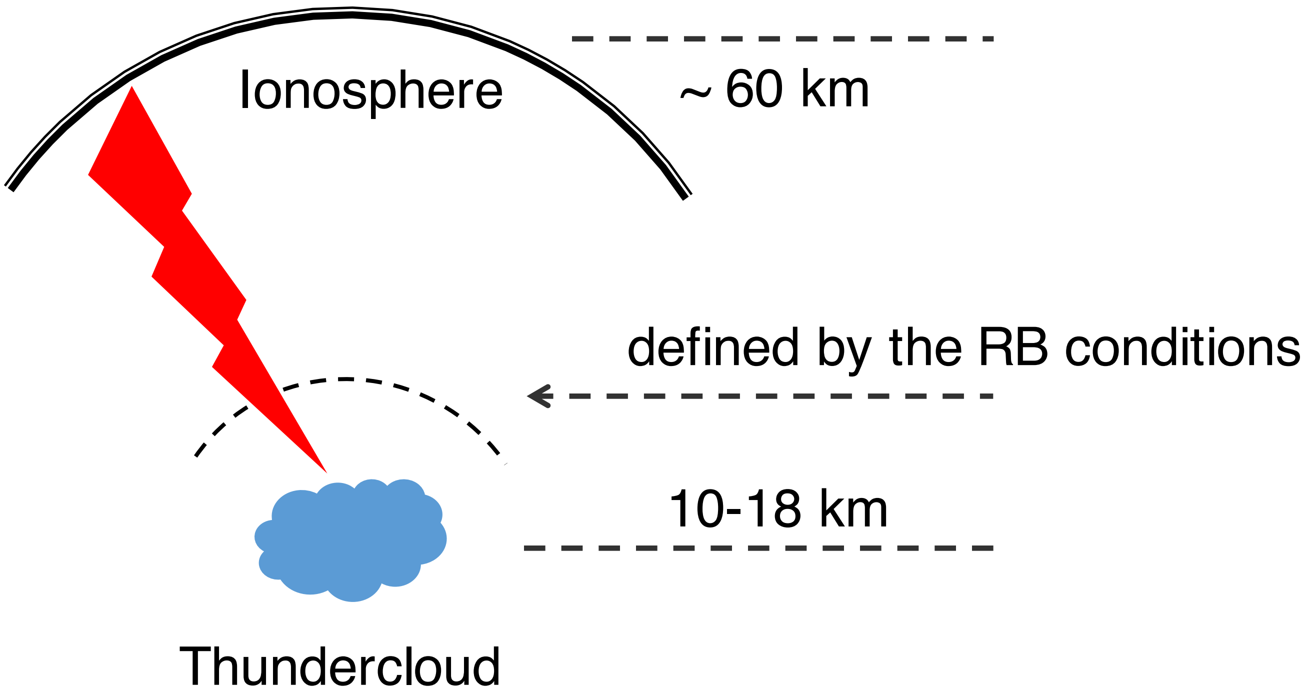
2) The characteristic sizes of clouds and their parts L are **always** much greater than the avalanche scales l_a;

3) The flux of **secondary cosmic ray seed electrons** is very large. At 4-8 km its attitude average flux density 🏭~ 10^3 m^{-2} s^{-1}. Typical mean energies are equal to 0.1-10 MeV.

*A.V. Gurevich and K.P. Zybin 2001 Phys.-Usp. 44 1119

Aims

To perform the direct numerical simulation of large-scale gas discharge (here "blue jet") in terms of physical kinetics. Namely, we need to compute the EDF at the discharge initiation and early development stages;



Kinetic model outline*

- Electrons. Relativistic Boltzmann equation for EDF

$$\gamma(p)\left(\frac{\partial f(\vec{x},\vec{p},t)}{\partial t}+\frac{\vec{p}}{m\gamma(p)}\frac{\partial f(\vec{x},\vec{p},t)}{\partial \vec{x}}-q\left\{\vec{E}(\vec{x},t)+\frac{\vec{p}\times\vec{B}}{m\gamma(p)}\right\}\frac{\partial f(\vec{x},\vec{p},t)}{\partial \vec{p}}\right)=Q_c\left[(\vec{x},\vec{p},t)\right]$$

- Ions. Continuity equations with drift-diffusion approximation (if needed)

$$\frac{\partial n_+}{\partial t}+\nabla\vec{\Gamma}_+=\int_{-\infty}^{\infty}Q_c\left[f(\vec{x},\vec{p},t)\right]d\vec{p},$$

- Electromagnetic field. Maxwell's equations

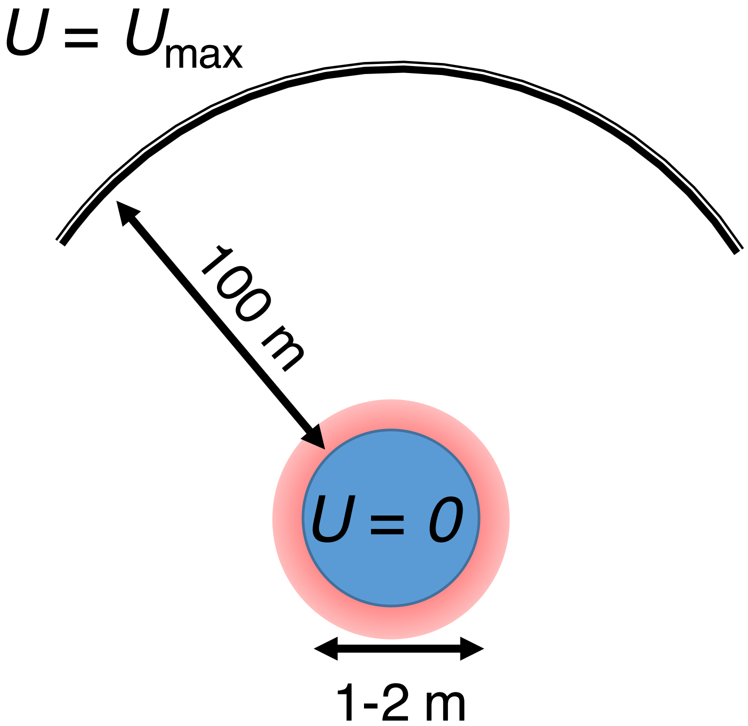
$$\nabla\vec{E}=\frac{q}{\varepsilon_0}[n_+-n_-],\quad \nabla\times\vec{E}=-\frac{\partial\vec{B}}{\partial t},\quad \nabla\times\vec{B}=\vec{j}+\varepsilon_0\frac{\partial\vec{E}}{\partial t},\quad \nabla\vec{B}=0$$

where

$$n_-(\vec{x},t)=q\int_{-\infty}^{\infty}f(\vec{x},\vec{p},t)\,d\vec{p},\quad \vec{j}_-(\vec{x},t)=\frac{q}{m}\int_{-\infty}^{\infty}f(\vec{x},\vec{p},t)\frac{\vec{p}}{\gamma(p)}d\vec{p}$$

*A. V. Kozyrev, V. Y. Kozhevnikov, et al. // EPL, v. 114, no. 4 (2016), p. 45001
A. V. Kozyrev, V. Y. Kozhevnikov, et al. // EPL, v. 112, no. 1 (2015), p. 15001

Model parameters



1D spherically symmetric

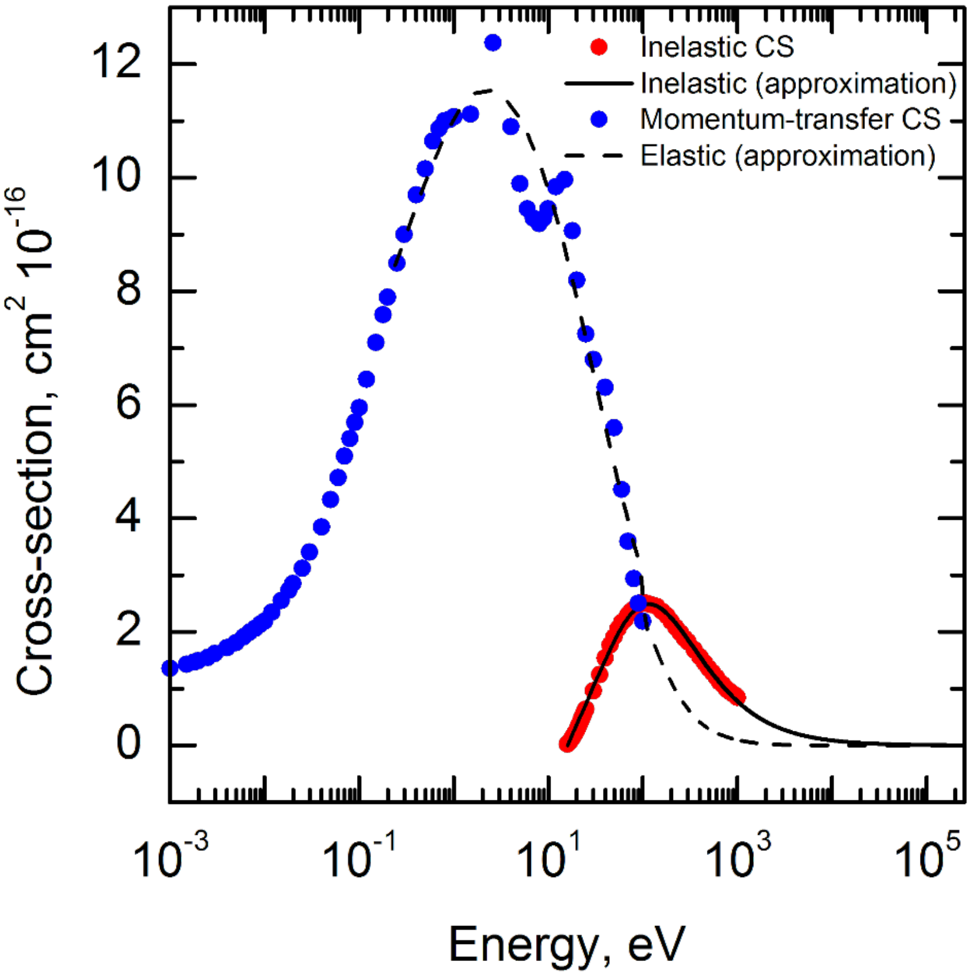
Pressure ~ 0.1 atm, temperature ~ 216 K

Interelectrode distance ~ 100 meters, cloud inhomogeneity size ~ 1 meter

Applied voltage $U_{max} = 5$ MV ($U_{br} = 50$ MV)

Initial electron mean energy [illegible]= 1 MeV, with the density n0 ~ 10^9 m^{-3} entirely localized near cloud

Elastic & Inelastic cross-sections (for air*)



Nelder approximation

$$\sigma(\varepsilon) = \frac{\varepsilon + a}{b_0 + b_1(\varepsilon + a) + b_2(\varepsilon + a)^2}$$

Elastic high-energy limit (Bethe extrapolation)

$$\sigma(\varepsilon) ; \frac{2Z}{\pi}\left(\frac{q^2}{4\varepsilon_0 \varepsilon}\right)^2\left(\frac{\varepsilon}{I_0} - 1\right)$$

Inelastic high-energy limit (Bethe extrapolation)

$$\sigma(\varepsilon) ; \pi\left(\frac{Zq^2}{4\pi\varepsilon_0 \varepsilon}\right)^2 \log\left(\frac{\varepsilon}{I_0}\right)$$

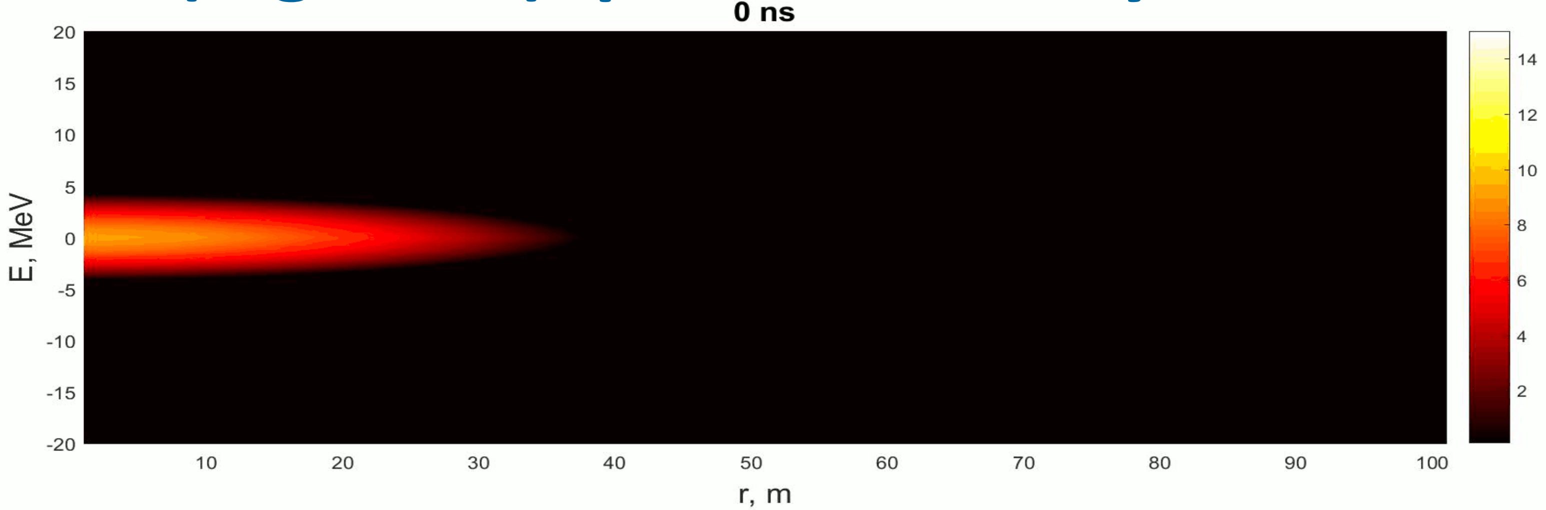
*Y. Itikawa // J. Phys. Chem. Ref. Data, v. 35, no 1 (2006)

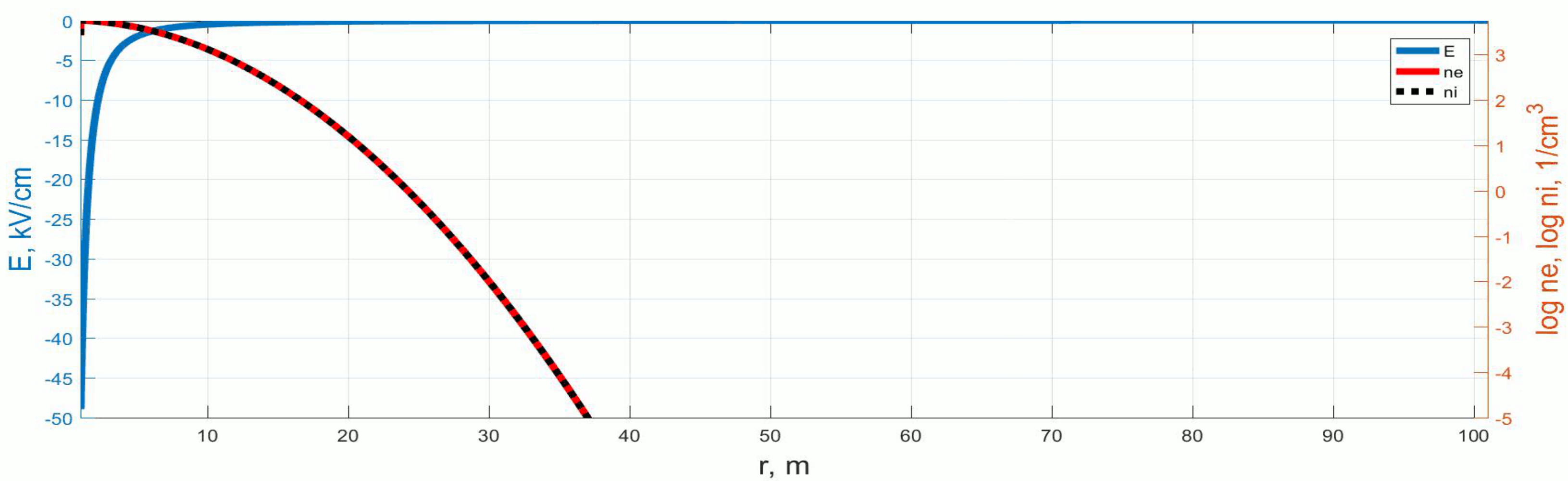
Numerical method

- ✓ Direct numerical solution of Boltzmann equation by using semi-Lagrangian method with second order splitting in time (Strang splitting);
- ✓ Cubic spline (Cheng-Knorr) & Linear interpolation schemes;
- ✓ Quasi-uniform "semi-infinity" 500x10001 phase-space computational grid;
- ✓ Average time step is 1-3 picoseconds.

G. Strang // SIAM J. Numer. Anal., v. 5, no. 3 (1968), pp. 506-517
C.Z. Cheng, G. Knorr // J. Comp. Phys., v. 22, no. 3 (1976), pp. 330-351
M. Lesur, Y. Idomura, and X. Garbet // Phys. Plasmas, 16, 092305 (2009)

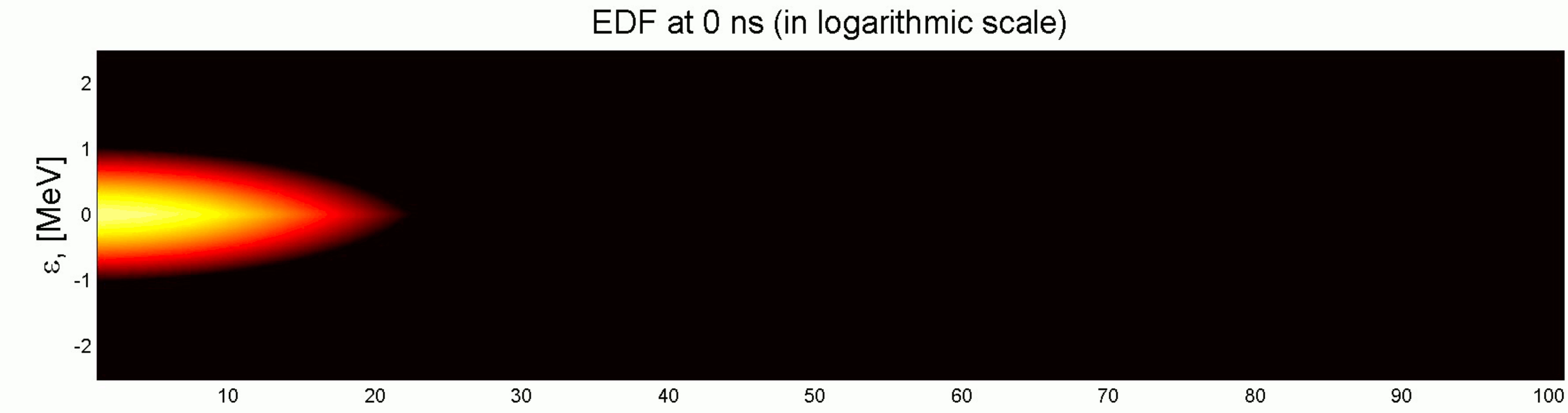
EDF (log scale), plasma density & electric field

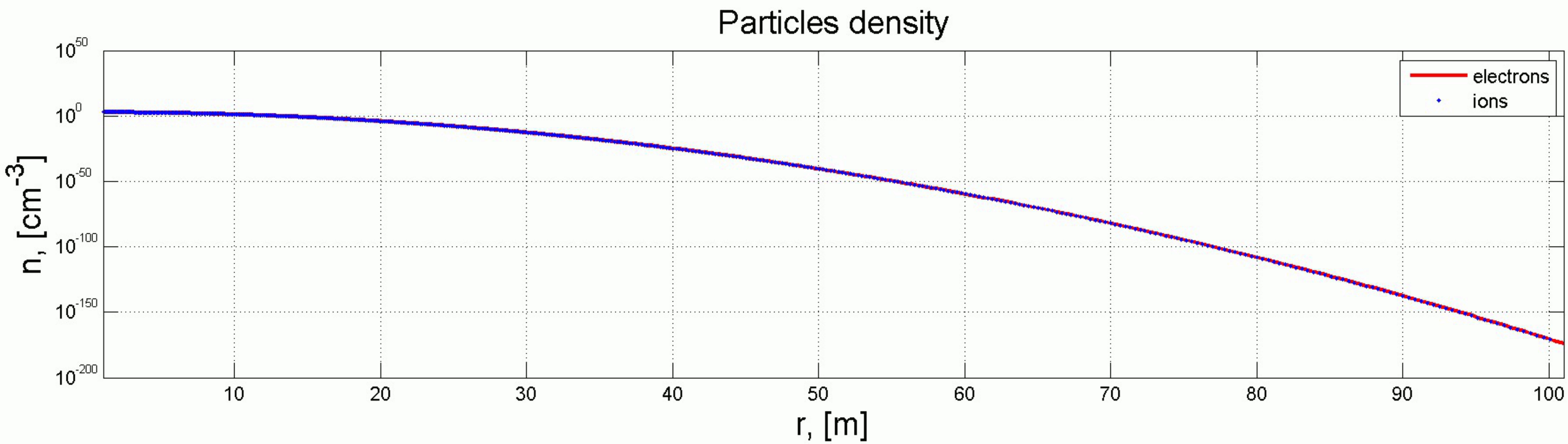




U_{max} = 5 MV, 🎁= 1 MeV @ 0.1 atm

Discharge in a “subcritical” electric field





U_{max} = 2 MV, = 1 MeV @ 0.1 atm

Summary

Within the framework of the kinetic theory we have obtained some agreement with asymptotic theory of runaway breakdown influence on the upper-atmospheric discharge formation and initiation. Model provides the energy spectrum of runaway electrons as well as the detailed time-dependent discharge EDF structure.

Future work to be done:

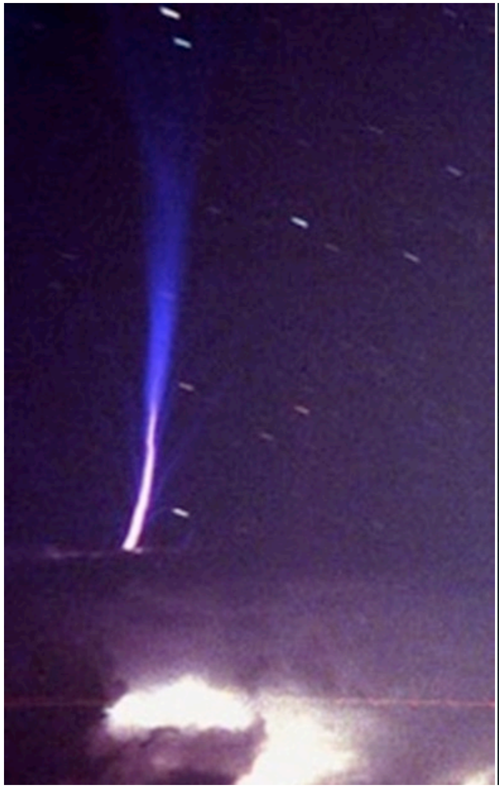
- Investigate the influence of the initial EDF on the discharge initiation and its formation;
- Simulate the "electrodeless" TLE forms, e.g. “elfes”;
- 2D & 3D hybrid models…

Instead of a conclusion: Apokampic discharge*

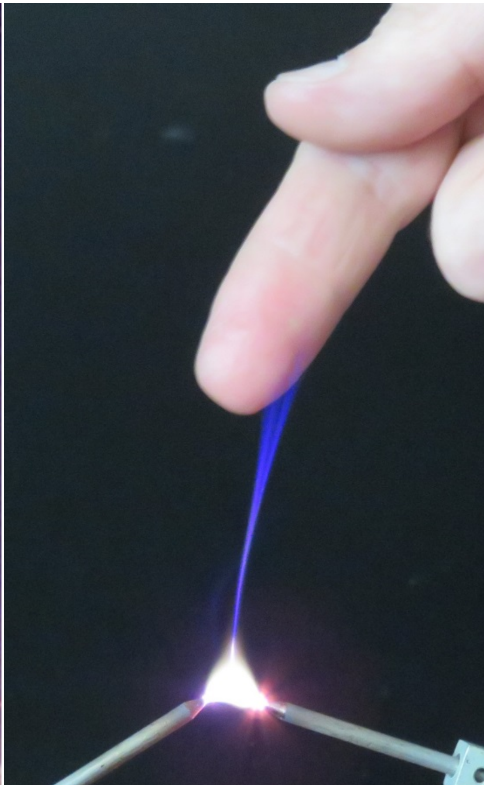
TLE origin 📹Runaway breakdown?

Apokampic discharge (from Greek *από* - “off” and *καμπη* - “bend”) - the stable plasma jet developing perpendicular to the bending point of the pulsed arc discharge channel between two electrodes.

Following the high-speed recording, it was discovered that apokamp channel consists of a set of plasma bullets moving with supersonic velocity of about 100–220 km/s.



Blue jet
(18 km altitude
with the tip at 35 km)

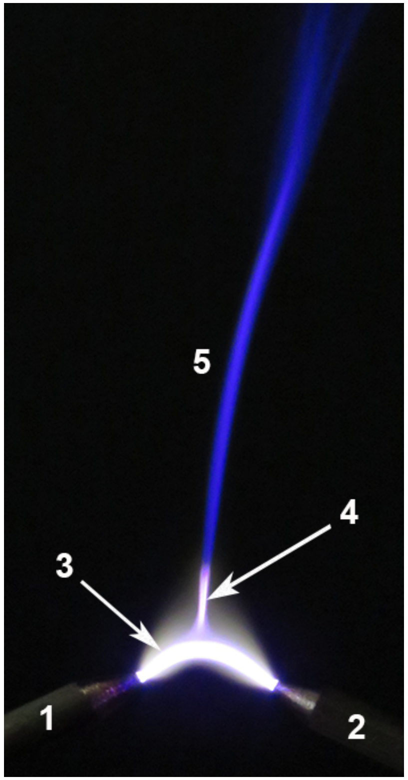


Apokamp

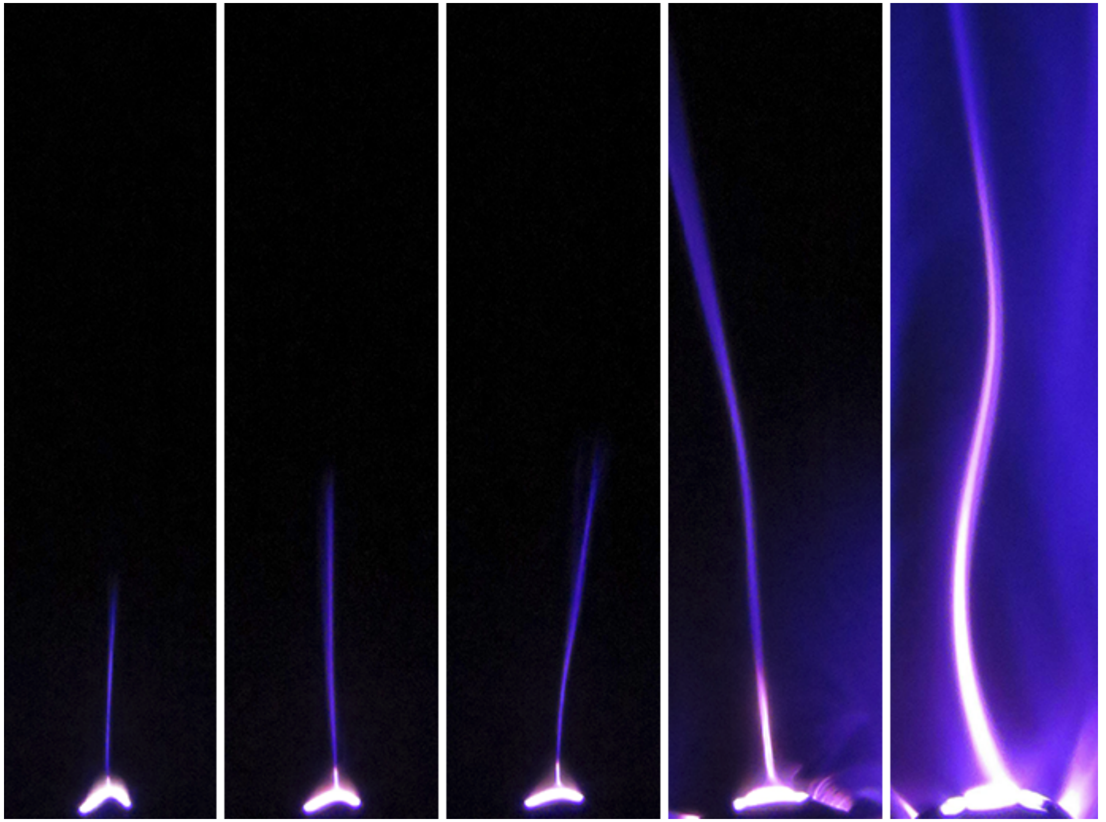
*E. A. Sosnin et al. // JETP Letters, vol. 103, no. 12, pp. 761–764, (2016)
E. A. Sosnin et al. // EPJ D, vol. 71, no. 2, (2017)

IEEE

Instead of a conclusion: Apokampic discharge



1 – floating potential electrode; 2 – high-voltage electrode; 3 – pulsed-periodic arc discharge channel; 4 – bright process; 5 – apokamp channel.



520 420 300 150 30

pressure in Torr

*E. A. Sosnin et al. // JETP Letters, vol. 103, no. 12, pp. 761–764, (2016)
E. A. Sosnin et al. // EPJ D, vol. 71, no. 2, (2017)

IEEE

Thank you!