Monte Carlo Model of Runaway Electrons in the Mesosphere

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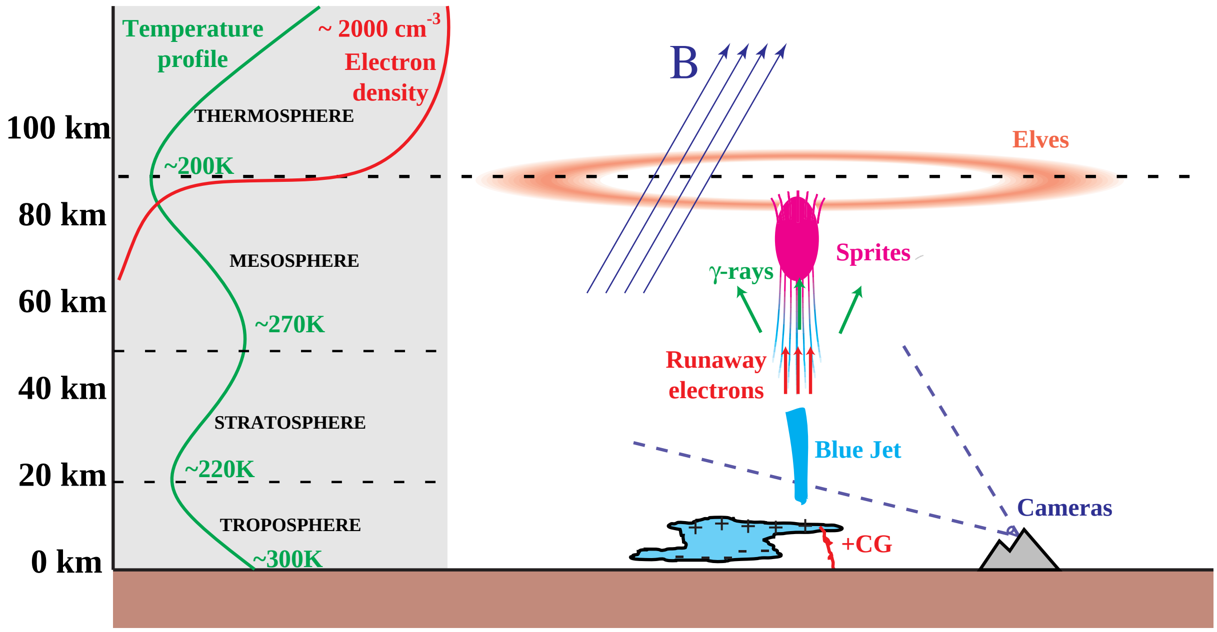
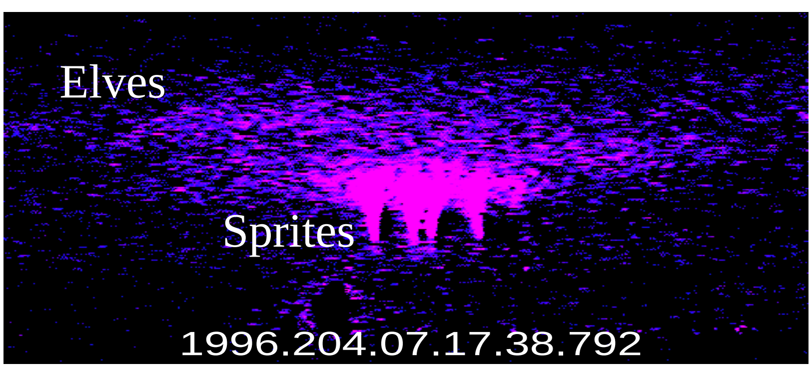
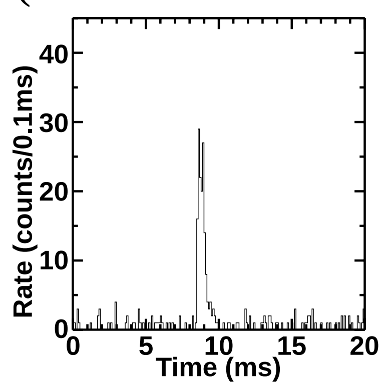
Lightning-mesosphere interaction phenomena



Red Sprites

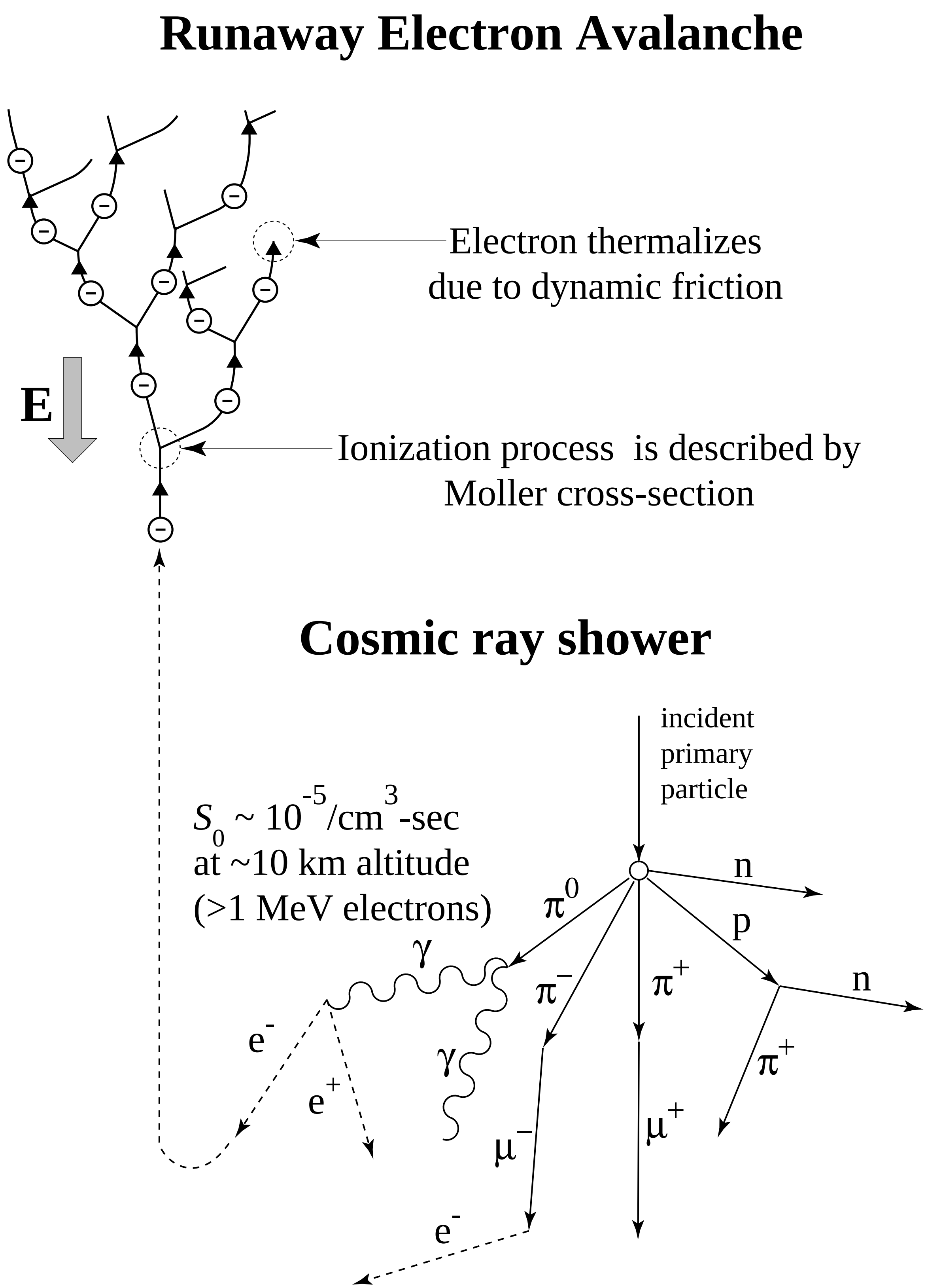


γ-ray flash
(BATSE observation)



Red Sprites:
- altitude range ~50-90 km
- lateral extent ~5-10 km
- occur ~1-5 ms after +CG discharge
- last up to several 10 ms

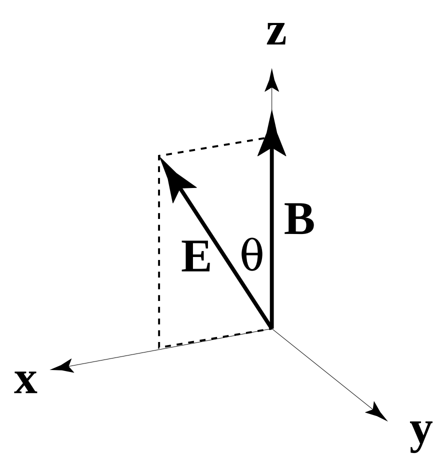
Terrestrial γ-ray flashes:
- last ~1 ms
- were correlated with thunderstorms
[*Inan et al.*, 1996]


Runaway Electron Avalanche
Electron thermalizes
due to dynamic friction
E
Ionization process is described by
Moller cross-section
Cosmic ray shower
incident
primary
particle
$S_0 \sim 10^{-5}$/cm^3-sec
at ~10 km altitude
(>1 MeV electrons)
n
π^0
p
γ
π^-
π^+
n
e^-
e^+
γ
π^+
μ^-
μ^+
e^-

Monte Carlo simulation

Previous runaway avalanche models:

- analytical [*Gurevich et al.*, 1996; *Sizykh et al.*, 1993; *Bulanov et al.*, 1997];
- kinetic [*Symbalisty et al.*, 1997];
- Monte Carlo [*Shveigert*, 1988].



Equation of motion:

$$\frac{d\vec{p}}{dt} = -e\vec{E} - \frac{e}{m\gamma}[\vec{p} \times \vec{B}] + \vec{\Gamma}(t)$$

Production of new electrons:

$$P(\vec{p} \text{ creates } \vec{p}' \text{ in interval } d^3\vec{p}') = N_m Z_m d\sigma dt$$

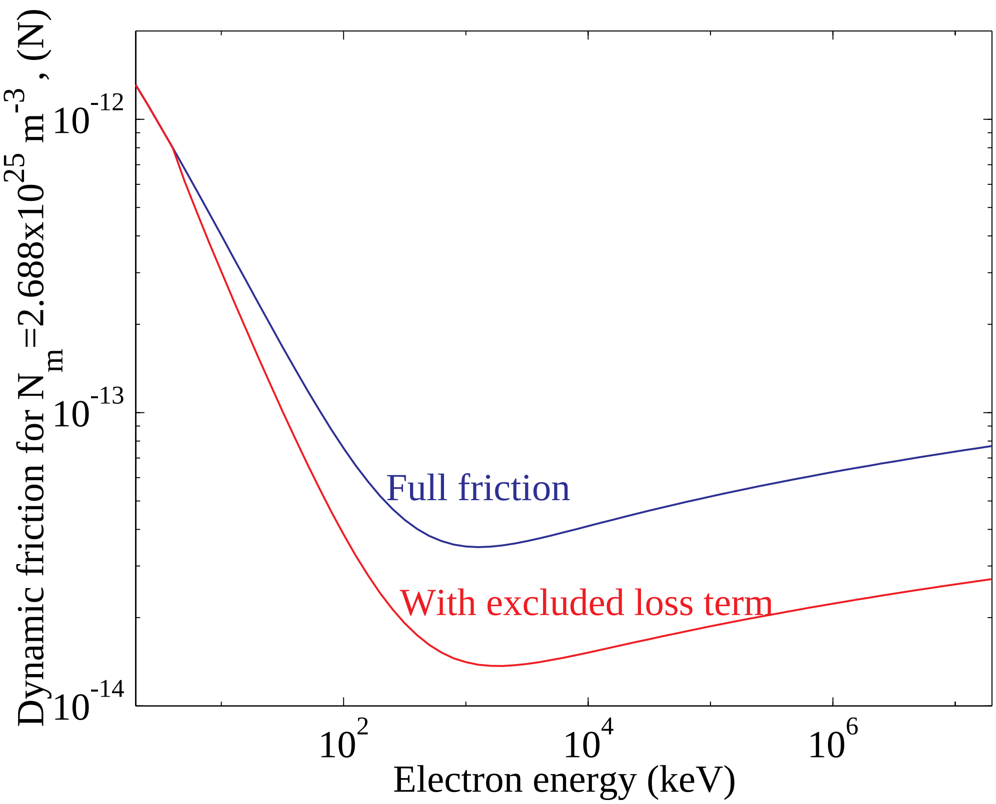
Angular diffusion part of $\Gamma(t)$:

$$\text{change direction by } \delta\theta = \sqrt{4D\Delta t}$$

Dynamic friction function

Exclude losses to created electrons from the friction:

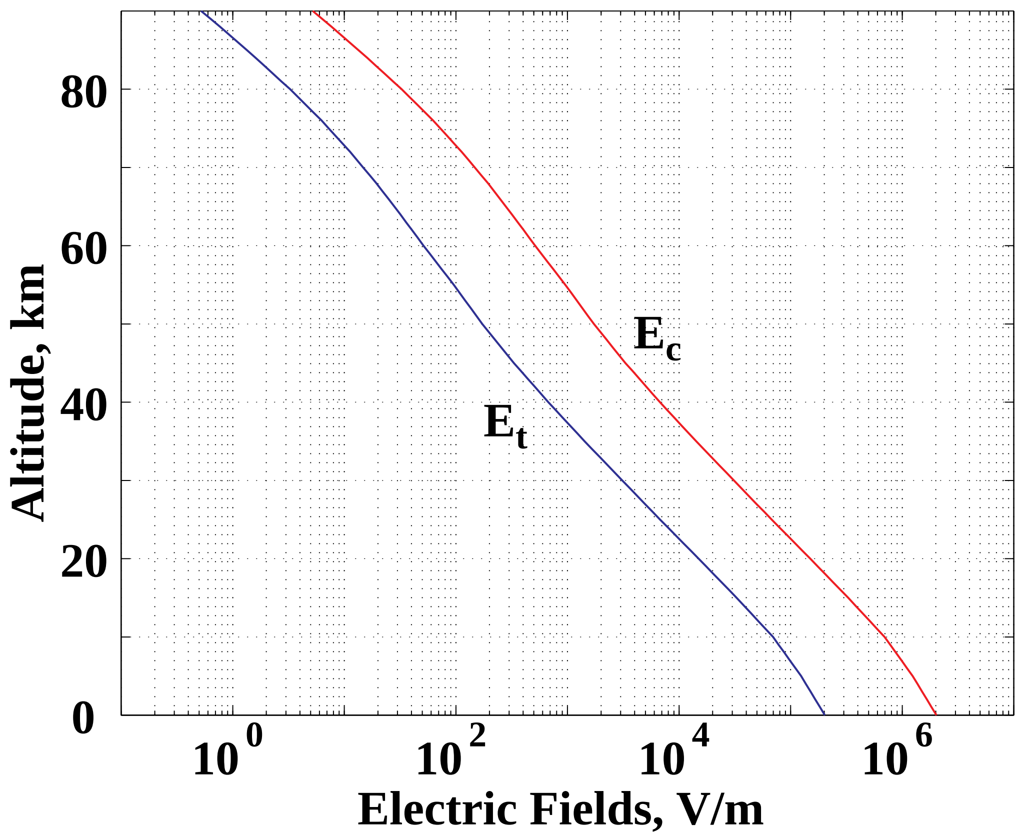
$$F_{d,\mathrm{excl}}(p) = F_d(p) - N_m Z_m \int_{\mathcal{E}_{\min}}^{\mathcal{E}-\mathcal{E}_{\min}} \Delta\mathcal{E}\sigma(\mathcal{E},\mathcal{E}')d\mathcal{E}'$$



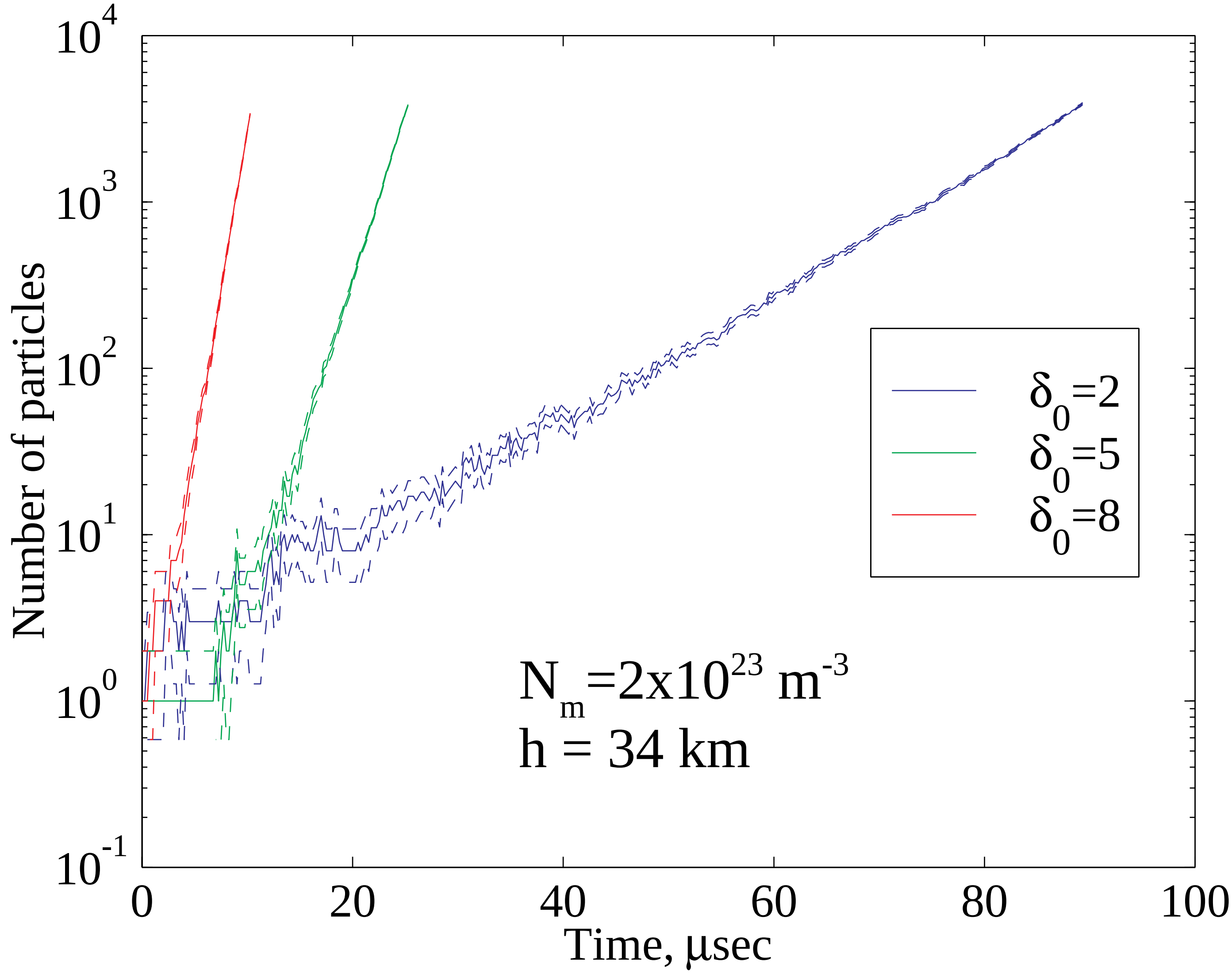
Runaway and conventional breakdown fields

$$F_d \sim N_m$$

$$E_t = F_{d,\min} / e$$



Growth of the number of particles for different parameters δ_0=E/E_t



Comparison of different predictions of runaway electron growth rate $1/\tau_i$

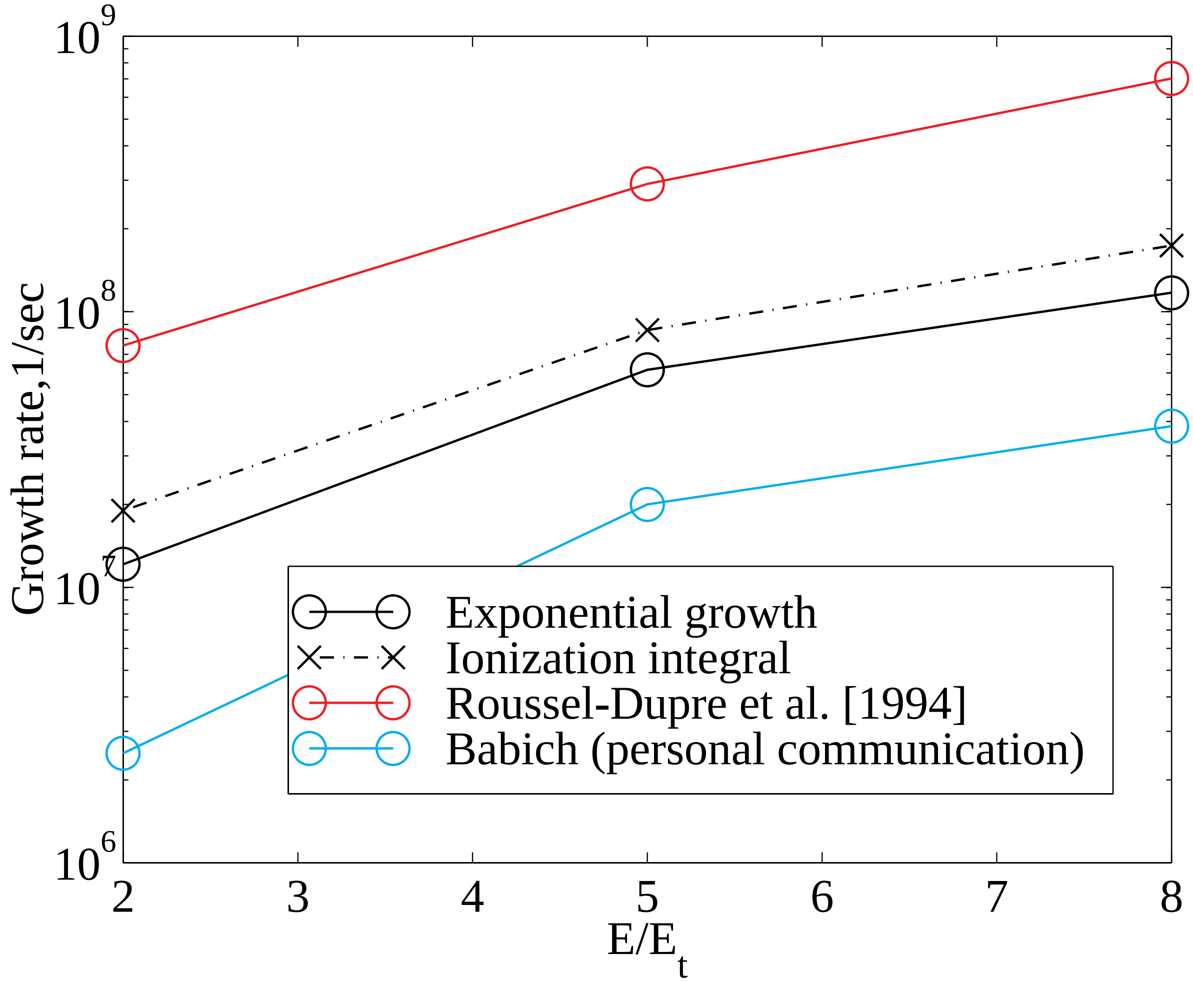
Two ways to calculate $1/\tau_i$:

1. Exponential growth of electron number:

$$N_R(t) \sim e^{t/\tau_i}$$

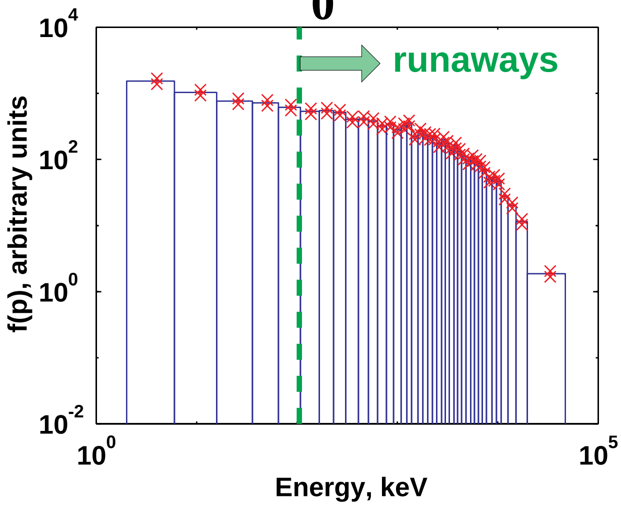
2. Ionization integral:

$$\frac{1}{\tau_i} = \frac{\partial N_R/\partial t}{N_R} = \frac{\int_{\substack{\text{REL}\\ \text{producers}}} N_m v \sigma_{\text{tot}} f(\vec{p}) d^3\vec{p}}{\int_{\text{REL}} f(\vec{p}) d^3\vec{p}}$$

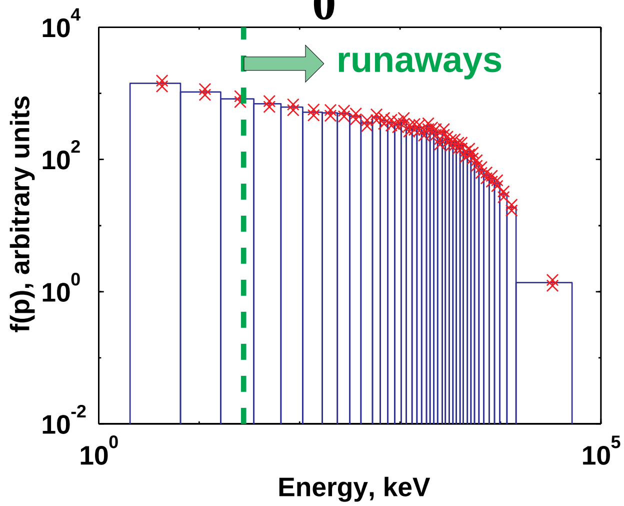


Electron distribution function without magnetic field for different $\delta_0=E/E_t$

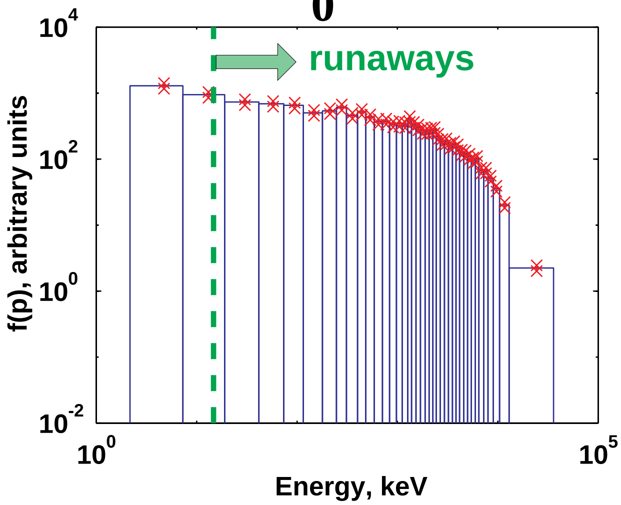
$\delta_0=2$



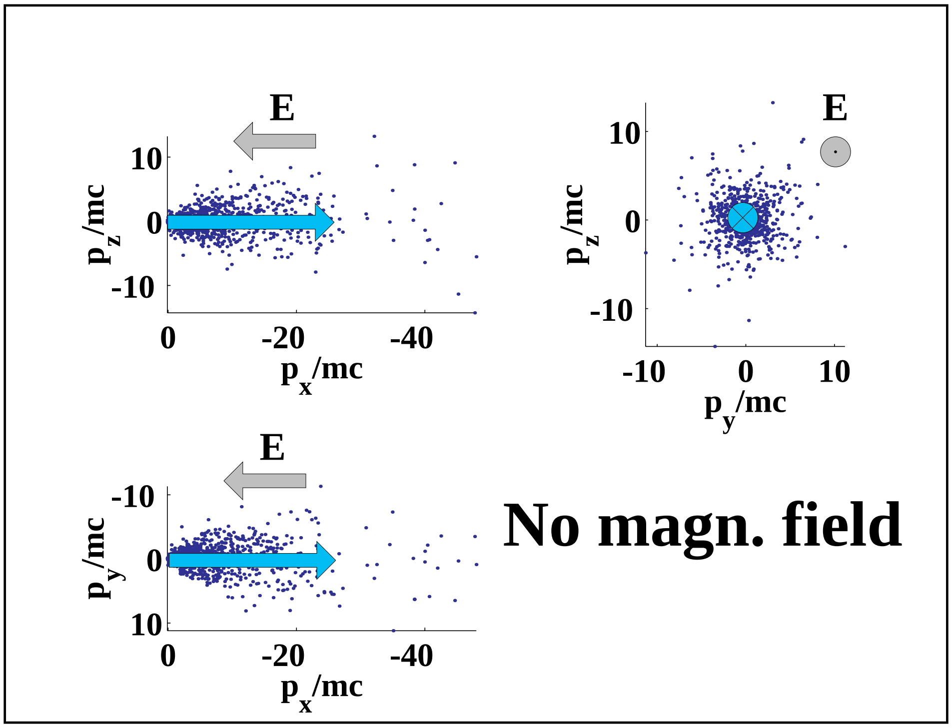
$\delta_0=5$

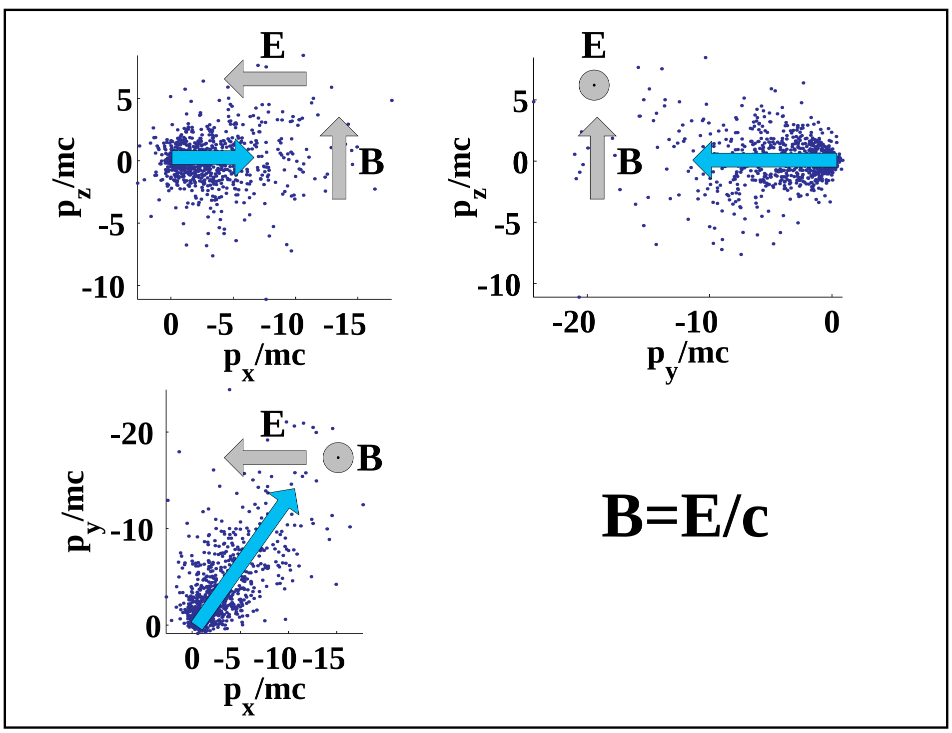


$\delta_0=8$



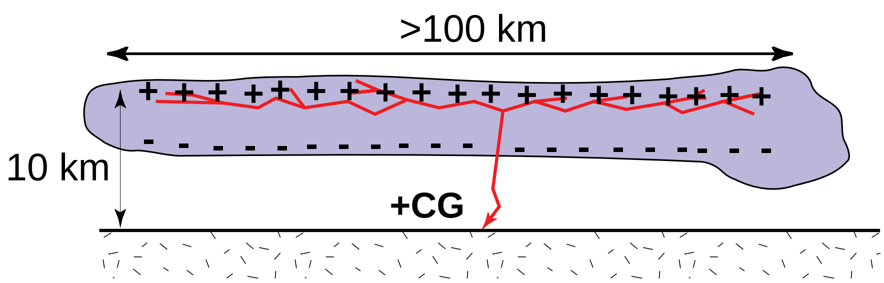
Electrons in momentum space for orthogonal E and B
$E=5E_t$





B=2E/c: No avalanche

Upper atmosphere model

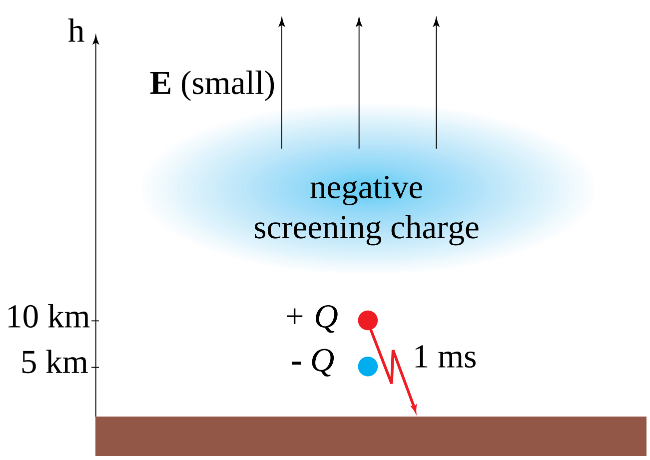


- cartesian (translationally symmetric along y axis)
- quasielectrostatic [*Pasko et al.*, 1997]
- fluid model for runaway electrons [*Lehtinen et al.*, 1997]

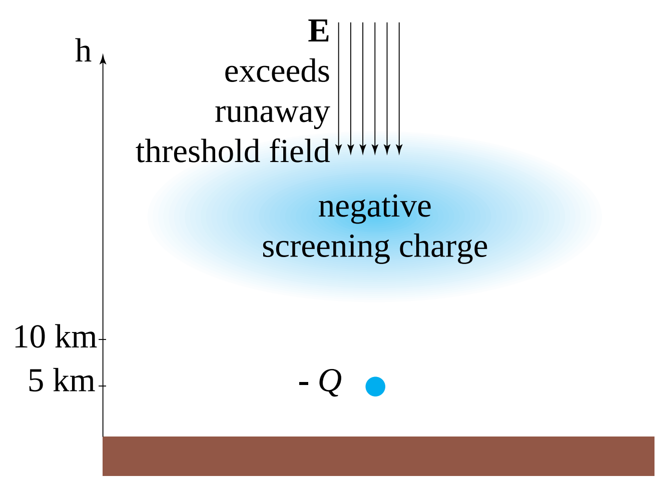
Dimensionless parameters for runaway velocity and rate:

$$\delta_0 = E/E_t, \quad \eta_0 = cB/E_t, \quad \mu_0 = \cos(\vec{E}, \vec{B})$$

BEFORE DISCHARGE

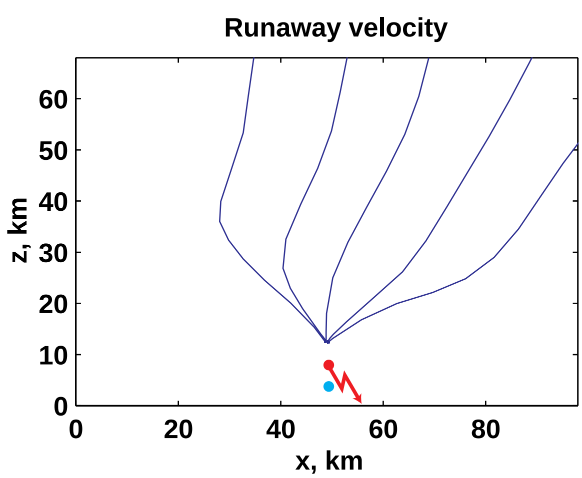


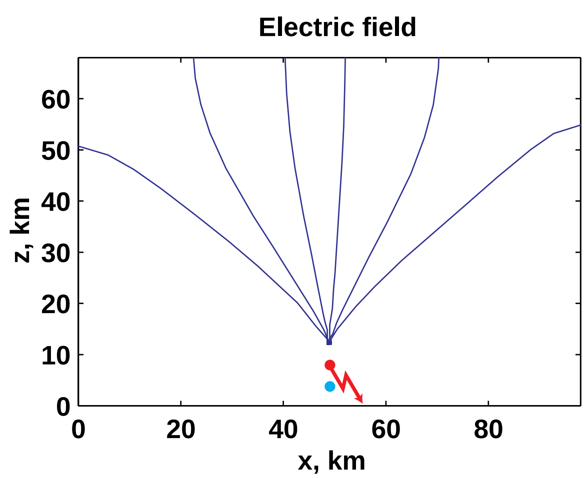
AFTER DISCHARGE

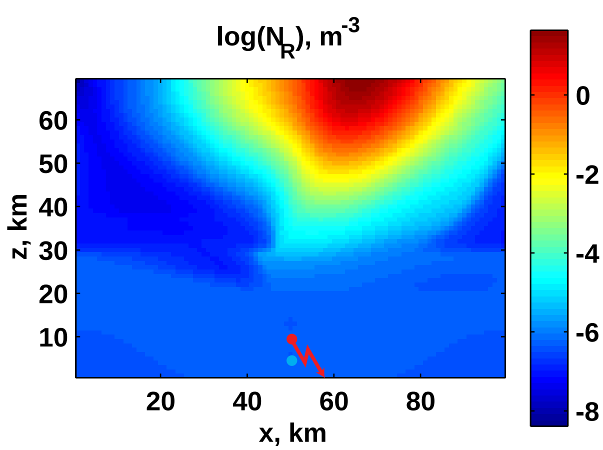


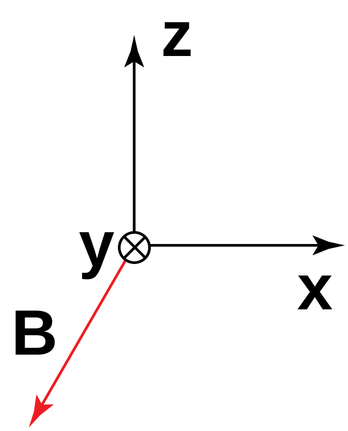
Runaway electron motion in presence of E and B: 1. B lies in (x,z) plane

Q = 8 C/km



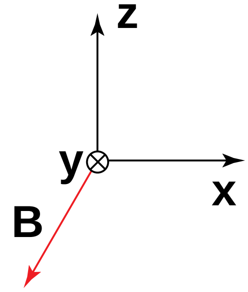


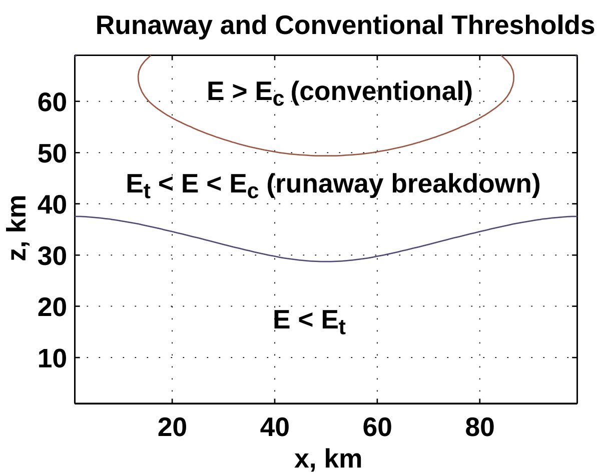


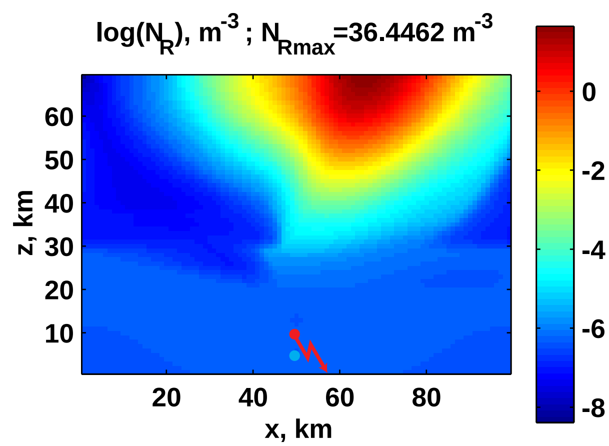


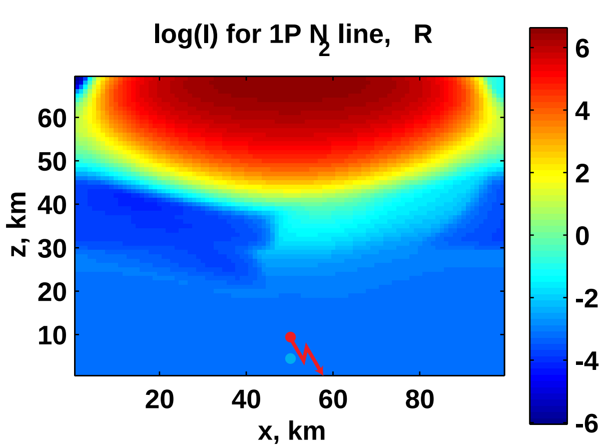
2D structure of runaway electron density and optical emissions in the First Positive Band of N_2 at t = 3ms:
1. B lies in (x,z) plane

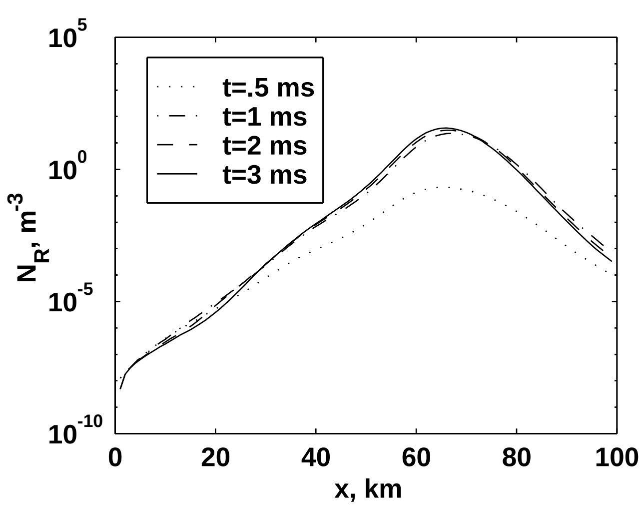
Q = 8 C/km





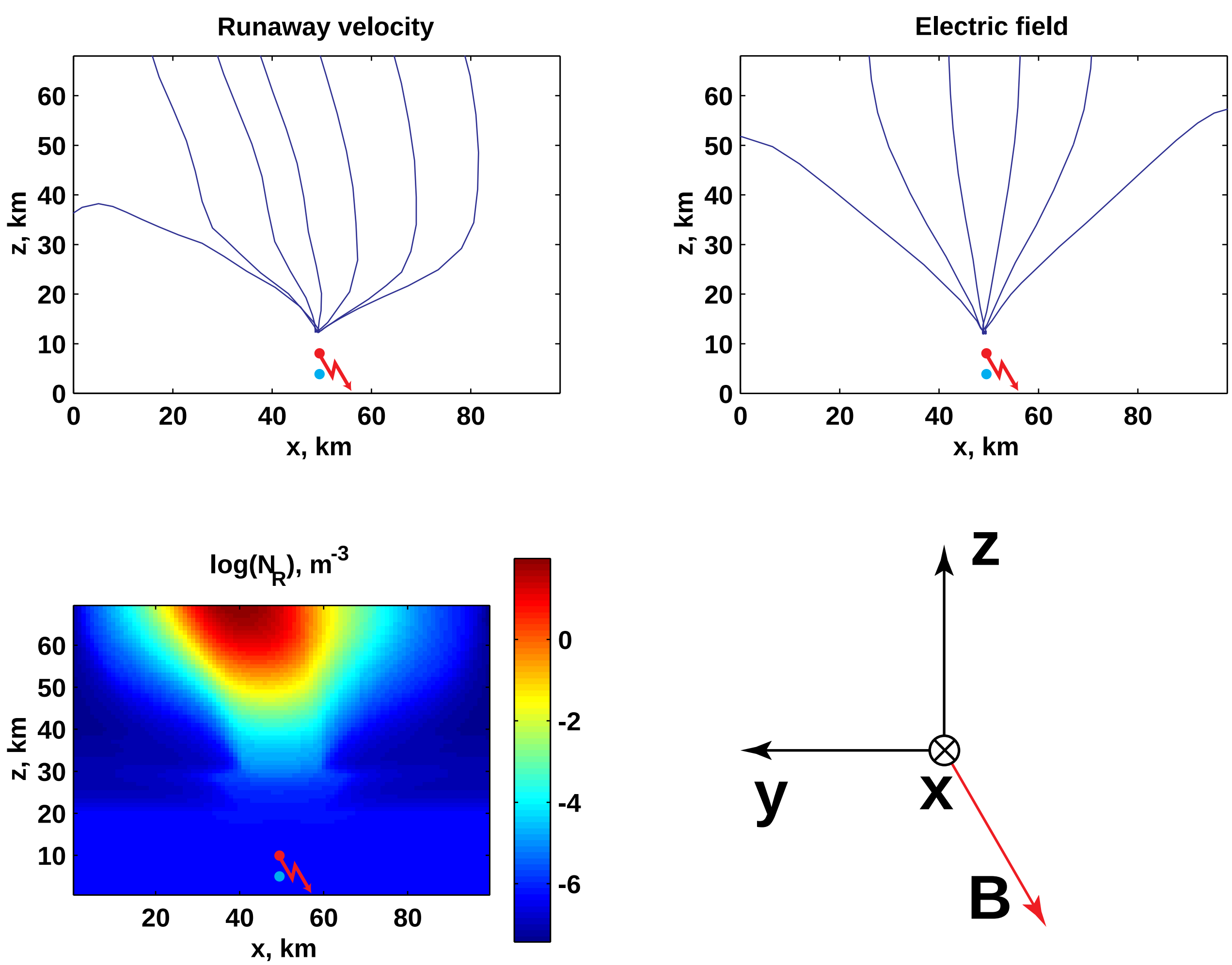






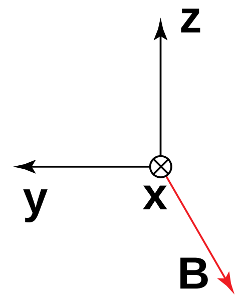
Runaway electron motion in presence of E and B: 2. B lies in (y,z) plane

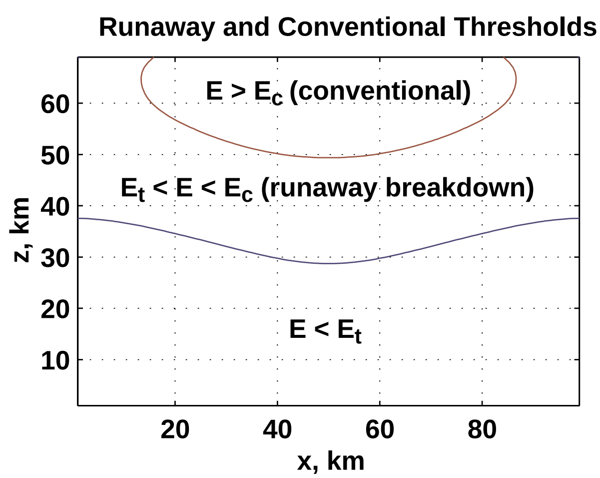
Q = 8 C/km

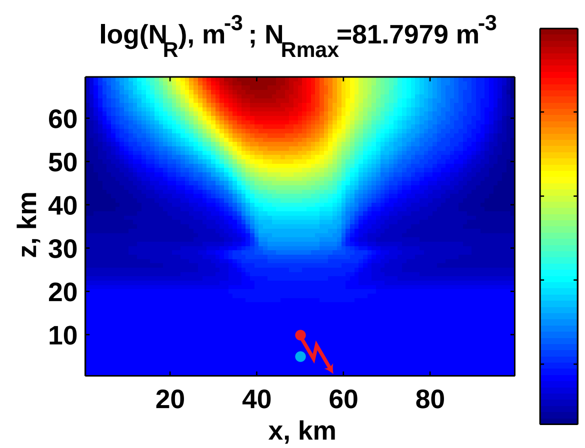


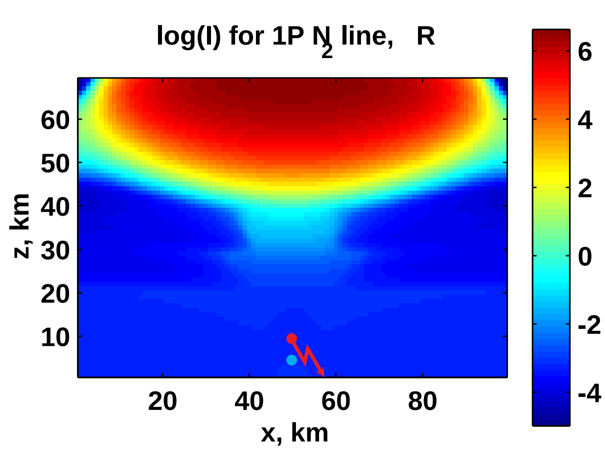
2D structure of runaway electron density and optical emissions in the First Positive Band of N_2 at t = 3ms:
2. B lies in (y,z) plane

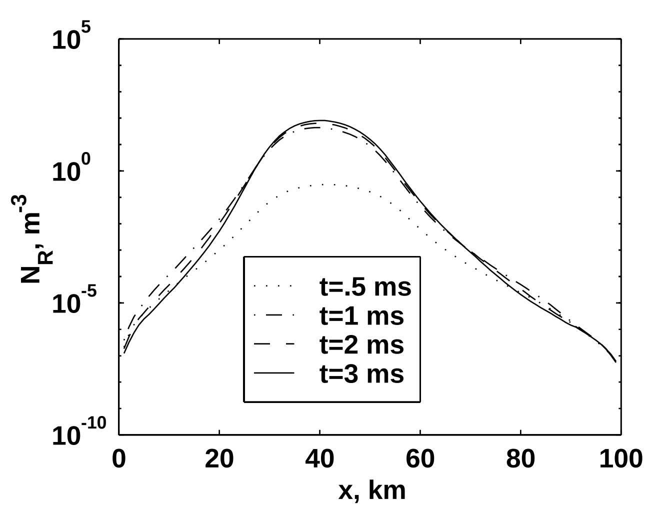
Q = 8 C/km



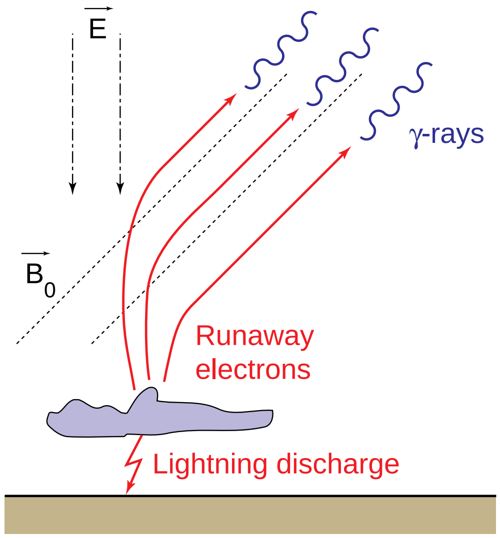


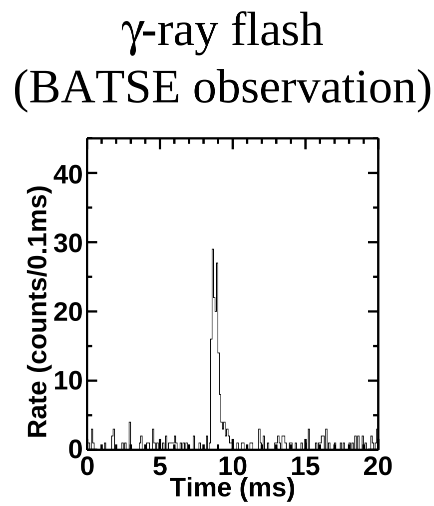




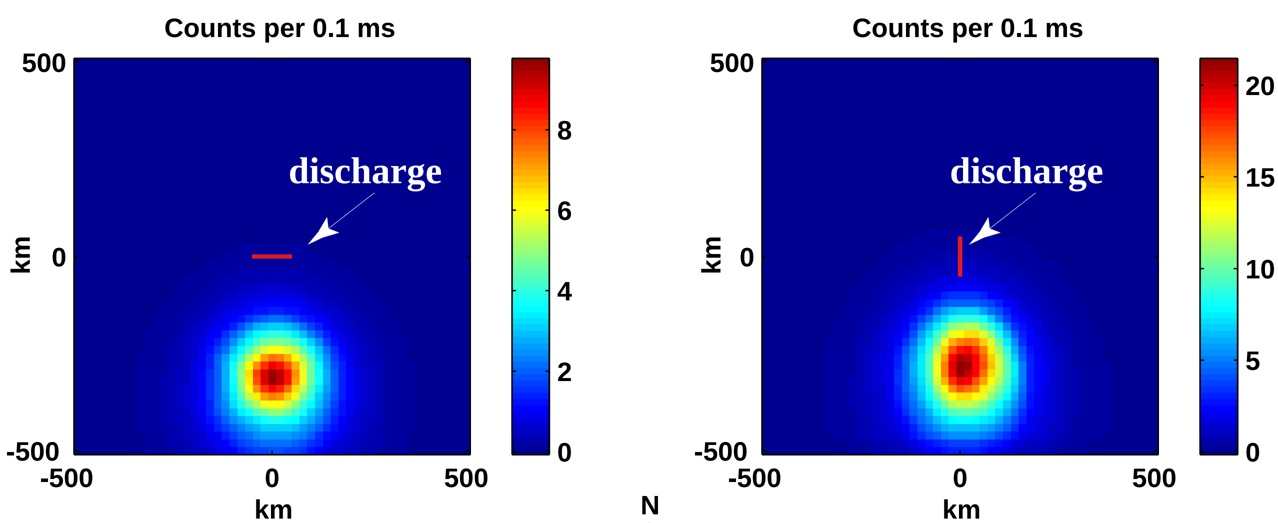


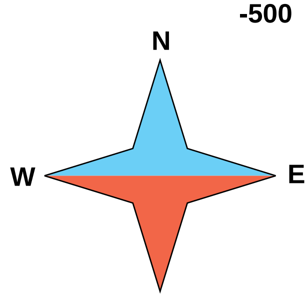
Terrestrial Gamma Ray Flashes





Simulated BATSE data at ~45° magnetic N latitutude in energy interval 100-300 keV





Conclusions

- We calculated uniform runaway electron avalanche rates in constant electric and magnetic fields and compared them to previously done work.
- We modelled runaway breakdown due to a positive return stroke from a laterally extensive thundercloud using cartesian (translationally symmetric) model and a lookup table of calculated runaway electron velocities and avalanche rates.
- The geomagnetic field controls the motion of runaways at >35km at mid-latitudes, where most Sprites are observed, and close to equatorial region, where the terrestrial γ-ray flashes are observed.
- At mid-latitudes geomagnetic field doesn't retard the runaway electron avalanche since the angle between E and B is small.
- For sufficiently large discharge values, the REL-produced γ-rays flux values agree with BATSE data [*Fishman et al.*, 1994].

REFERENCES

Babich, L. P, et al. Numerical simulation of a nanosecond discharge in helium at atmospheric pressure, developing in the regime of runaway of electrons, *High Temperature, 33*, 190, 1995.

Babich, L. P, *personal communication.*

Bell, T. F., V. P. Pasko, and U. S. Inan, Runaway electrons as a source of red sprites in the mesosphere, *Geophys. Res. Lett., 22*, 2127, 1995.

Bethe, H. A., and J. Ashkin, *Experimental Nuclear Physics*, edited by E. Segrè, vol. 1, Wiley, New York, 1953.

Bulanov, S. V., M. Lontano, P. V. Sasorov, Ionization rate in the presence of runaway electrons, *Phys. Plasmas, 4*, 931, 1997.

Fishman G. J., P. N. Bhat, R. Malozzi, J. M. Horack, T. Koshut, C. Kouveliotou, G. N. Pendleton, C. A. Meegan, R. B. Wilson, W. S. Paciesas, S. J. Goodman, H. J. Christian, Discovery of intense gamma-ray flashes of atmospheric origin, *Science, 264*, 1313, 1994.

Gurevich, A. V., J. A. Valdivia, G. M. Milikh, and K. Papadopulous, Runaway electrons in the atmosphere in the presence of a magnetic field, *Radio Science, 31*, 1541, 1996.

Heitler, W., *The Quantum theory of radiation, 3rd ed.*, Clarendon, Oxford, 1954.

Inan, U. S., S. C. Reising, G. J. Fishman and J. M. Horack, On the association of terrestrial gamma-ray bursts with lightning and implication for sprites, *Geophys. Res. Lett., 23*, 1017, 1996.

Lehtinen, N. G., M. Walt, U. S. Inan, T. F. Bell and V. P. Pasko, γ-ray emission produced by a relativistic beam of runaway electrons accelerated by quasi-electrostatic thundercloud fields, *Geophys. Res. Lett., 23*, 2645, 1996.

Lehtinen, N.G., T. F. Bell, V. P. Pasko and U. S. Inan, A two-dimensional model of runaway electron beams driven by quasi-electrostatic thundercloud fields, *Geophys. Res. Lett., 24*, 2639, 1997.

Nemiroff, R. J., J. T. Bonnell and J. P. Norris, Temporal and spectral characteristics of terrestrial gamma flashes, *J. Geophys. Res., 102*, 9659, 1997.

Pasko, V. P., U. S. Inan, T. F. Bell and Yu. N. Taranenko, Sprites Produced by Quasi-Electrostatic Heating and Ionization in the Lower Atmosphere, *J. Geophys. Res., 102*, 4529, 1997a.

Pasko, V. P., U. S. Inan and T. F. Bell, Ionospheric Effects due to Electrostatic Thundercloud Fields, *to be submitted to JATP*, 1997b.

Risken, H. *The Fokker-Planck Equation, 2nd ed.*, Springer-Verlag, Berlin, 1989.

Roussel-Dupré, R. A., A. V. Gurevich, T. Tunnel and G. M. Milikh, Kinetic theory of runaway breakdown, *Phys. Rev., 49*, 2257, 1994.

Roussel-Dupré, R. A. and A.V. Gurevich, On runaway breakdown and upward propagating discharges, *J. Geophys. Res., 101*, 2297, 1996.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, M. J. Heavner, Preliminary results from the Sprites94 campaign: Red Sprites, *Geophys. Res. Lett., 22*, 1205, 1995.

Shveigert, V. A., Development of electron avalanche in strong electric fields, *Sov. J. Plasma Phys., 14*, 373, 1988.

Sizykh, S. V., Runaway electron production rate in gaseous discharges, *High Temperature, 31*, 1, 1993.

Taranenko, Y., and R. Roussel-Dupré, High altitude discharges and gamma-ray flashes: a manifestation of runaway air breakdown, *Geophys. Res. Lett., 23*, 571, 1996.