A TWO-DIMENSIONAL MODEL OF RUNAWAY ELECTRON BEAMS DRIVEN BY QUASI-ELECTROSTATIC THUNDERCLOUD FIELDS

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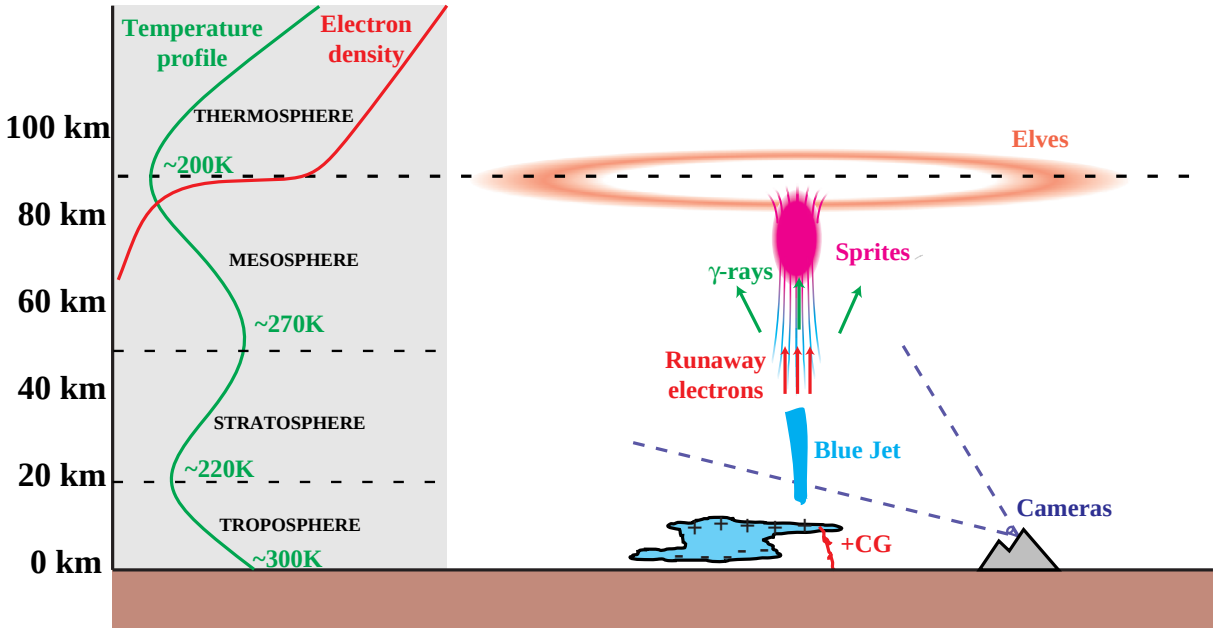
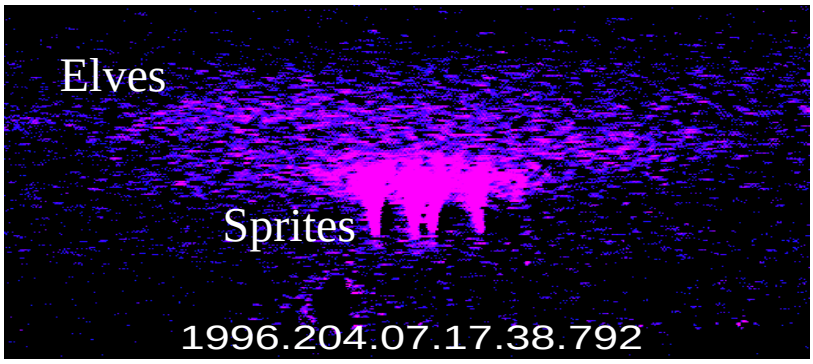
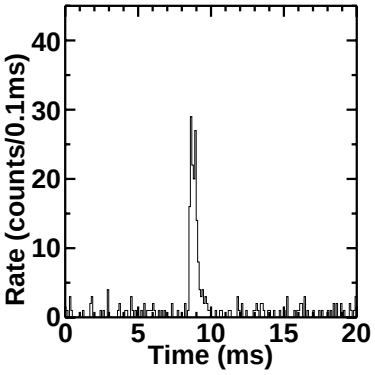
Lightning-mesosphere interaction phenomena



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

Literature

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.

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.

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.

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., in press*, 1997.

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

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

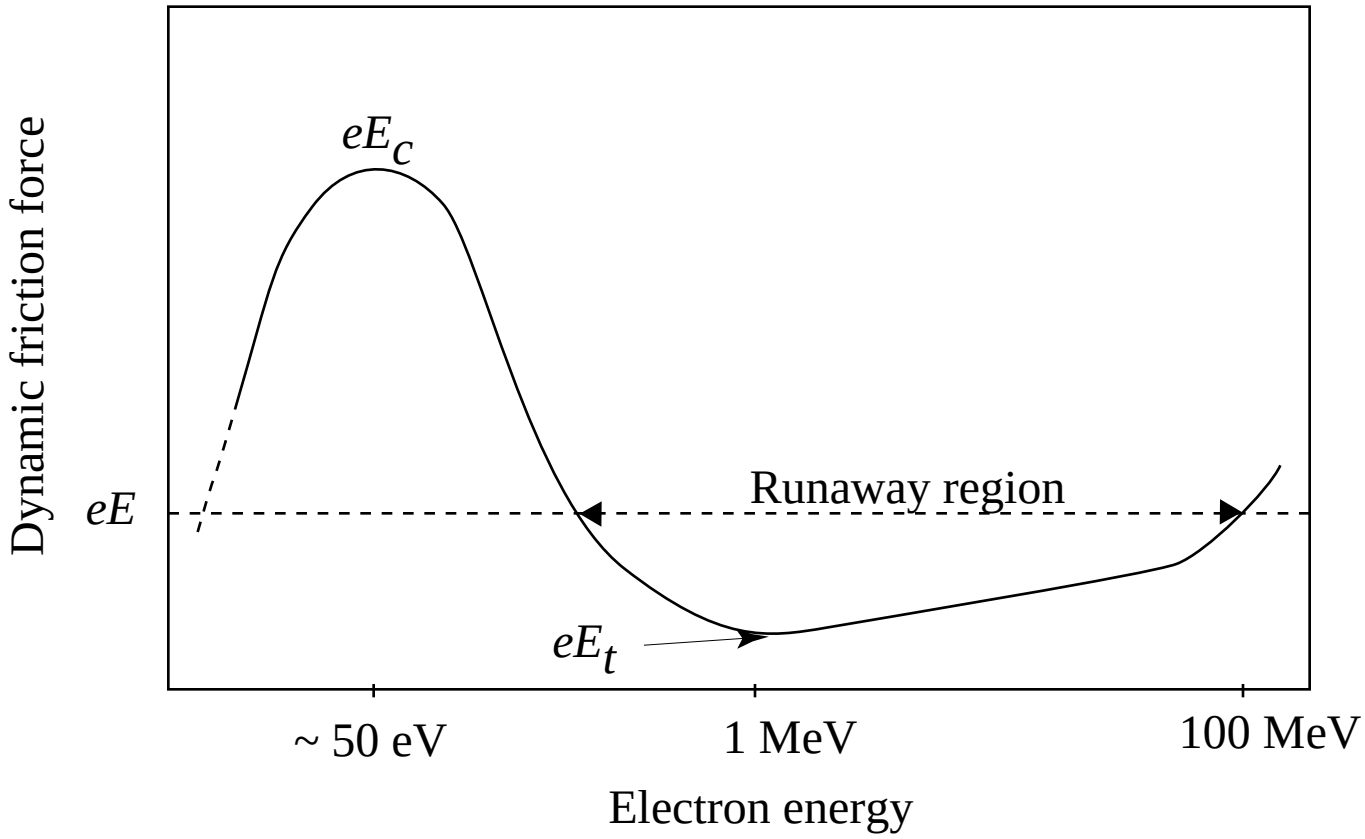
Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, M. J. Heavner, Preliminary results from the Sprites94 campaign: Red Sprites, *Geophys.Res. Lett., 22*, 1205, 1995.

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

Electron energy losses in the atmosphere

Dinamic friction force is due to inelastic collisions:

- excitation of molecules:
  - ¥ rotational
  - ¥ vibrational
  - ¥ optical emissions ~ 10 eV
- dissociation
- ionization > 10 eV

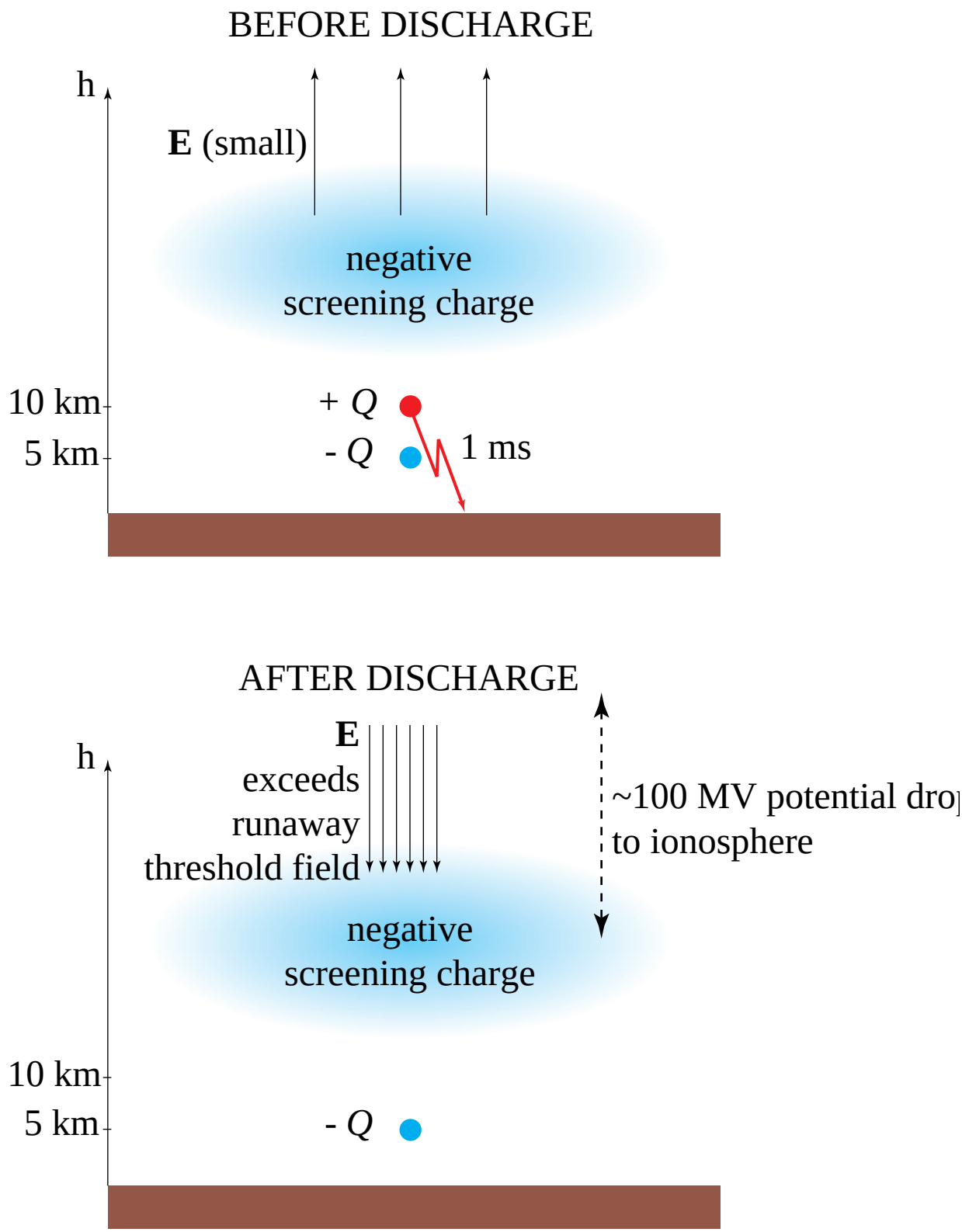


E_c - conventional avalanche breakdown field

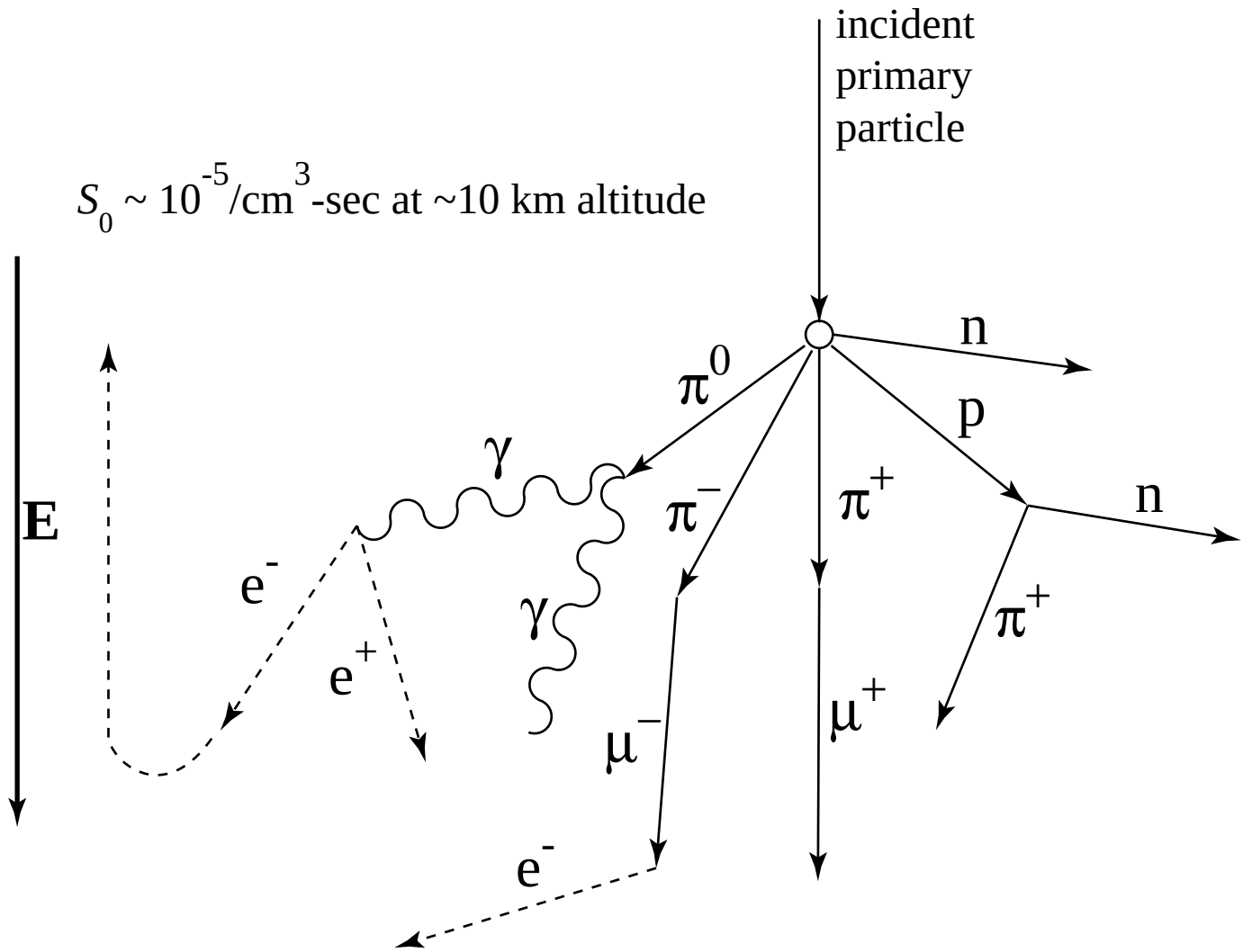
E_t - runaway threshold field

$E_c/E_t \sim 10$

Positive cloud-to-ground discharge (+CG)



Cosmic ray shower



THEORETICAL MODEL

- Quasi-electrostatic field:

$$\vec{E} = -\nabla\phi, \qquad \phi = \phi(\vec{r}, t)$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot\vec{J} + \nabla\cdot\vec{J}_R = \frac{\rho_s\sigma_0}{\epsilon_0}, \qquad \vec{J}_R = -e\vec{v}_R N_R$$

$$\nabla\cdot\vec{E} = \frac{\rho + \rho_s}{\epsilon_0}$$

  $\vec{J}_R$, $\vec{v}_R$, N_R — current, velocity and density of runaway electrons

  ρ_s — source thundercloud charge

- Runaway electrons:

$$\frac{\partial N_R}{\partial t} + \nabla\cdot(\vec{v}_R N_R) = \frac{N_R}{\tau_i} + S_o(z)$$

$$\dot{\vec{p}} = -e\vec{E} - \frac{e}{m\gamma}(\vec{p}\times\vec{B}) - \nu_R\vec{p}, \qquad \nu_R = \frac{F_D}{p}$$

  $1/\tau_i$ — runaway avalanche rate

  F_D — dynamic friction force

- Ionization produced by runaways:

$$\frac{\partial N_{es}}{\partial t} = (\nu_i - \nu_a)N_{es} + N_a v_R N_R \chi_{i0}$$

  N_{es} — density of low-energy electrons

  χ_{i0} — ionization cross-section

  N_a — density of atmospheric atoms

- Optical emissions (N_2 First Positive Band) are due to

  — thermal electrons, driven by the electric field,

  — suprathermal electrons ($\gtrsim 10$ eV), created by the runaways,

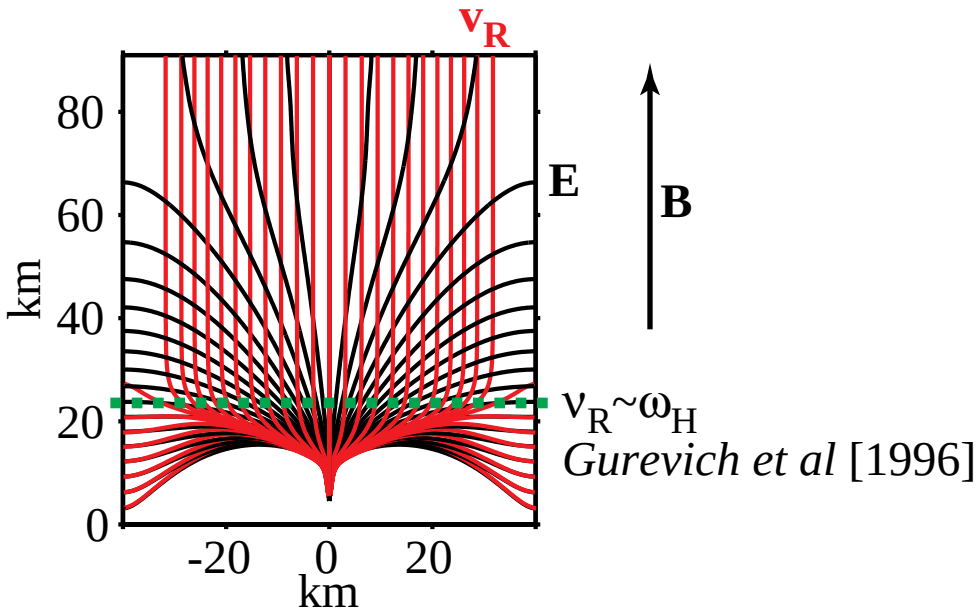
  and are calculated on the basis of known molecular excitation cross-sections and emission rates.

- γ-rays are calculated using Heitler bremsstrahlung cross-sections.

Runaway trajectories

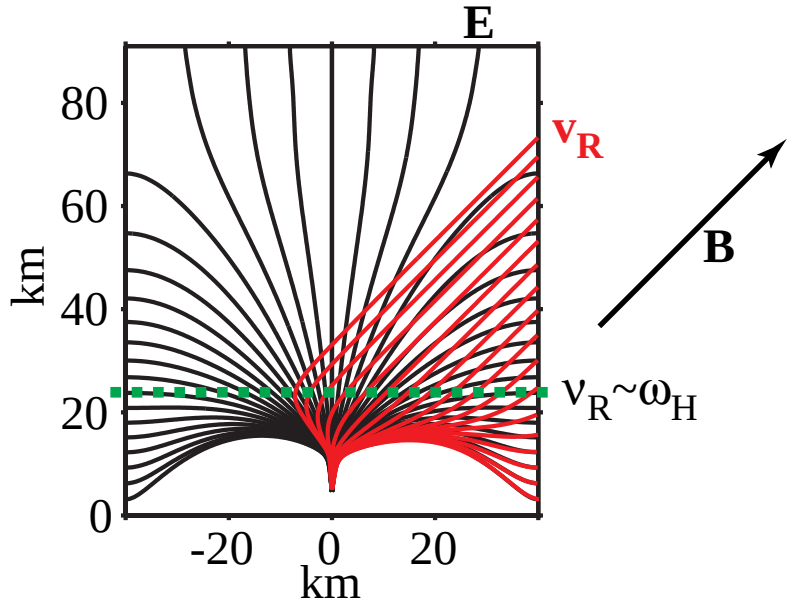
t=1.2 ms, *Q*=225 C

2-D MODEL



Gurevich et al [1996]

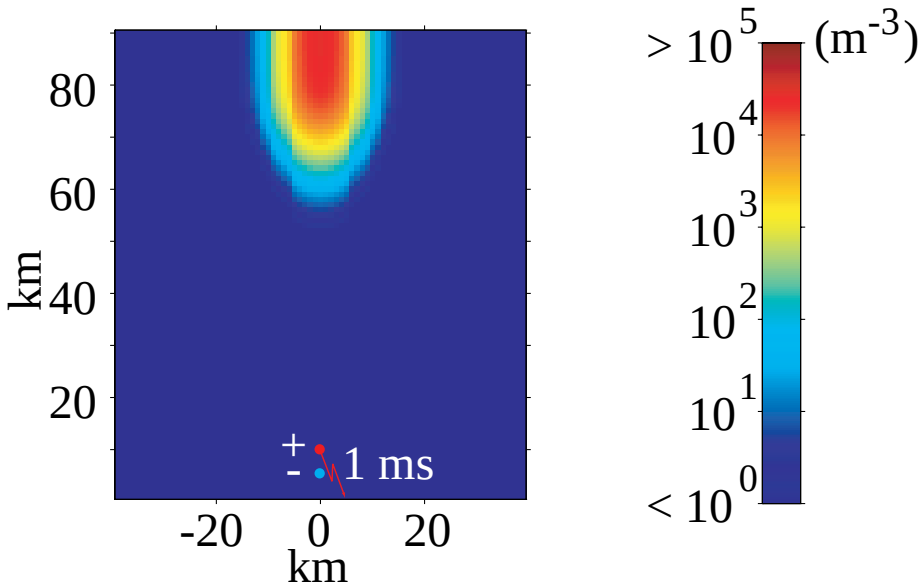
demonstration of runaway trajectories for tilted geomagnetic field



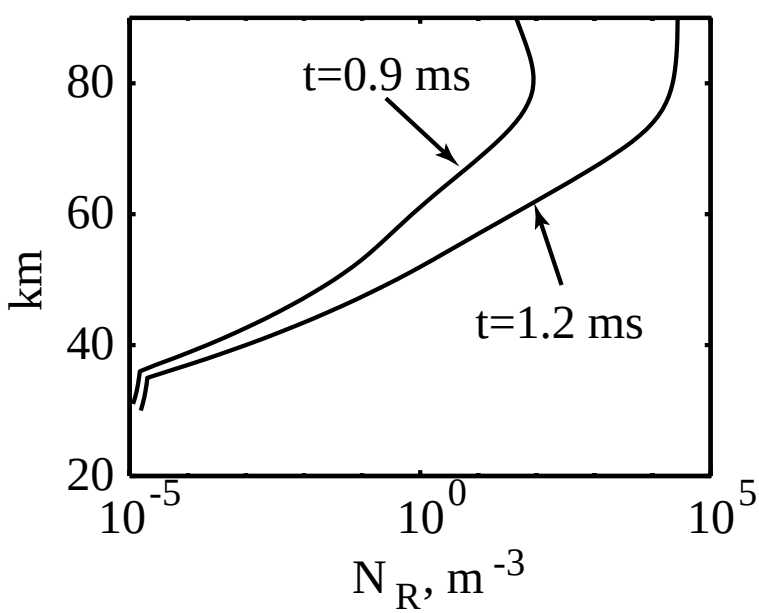
Runaway electron density

Q=225 C

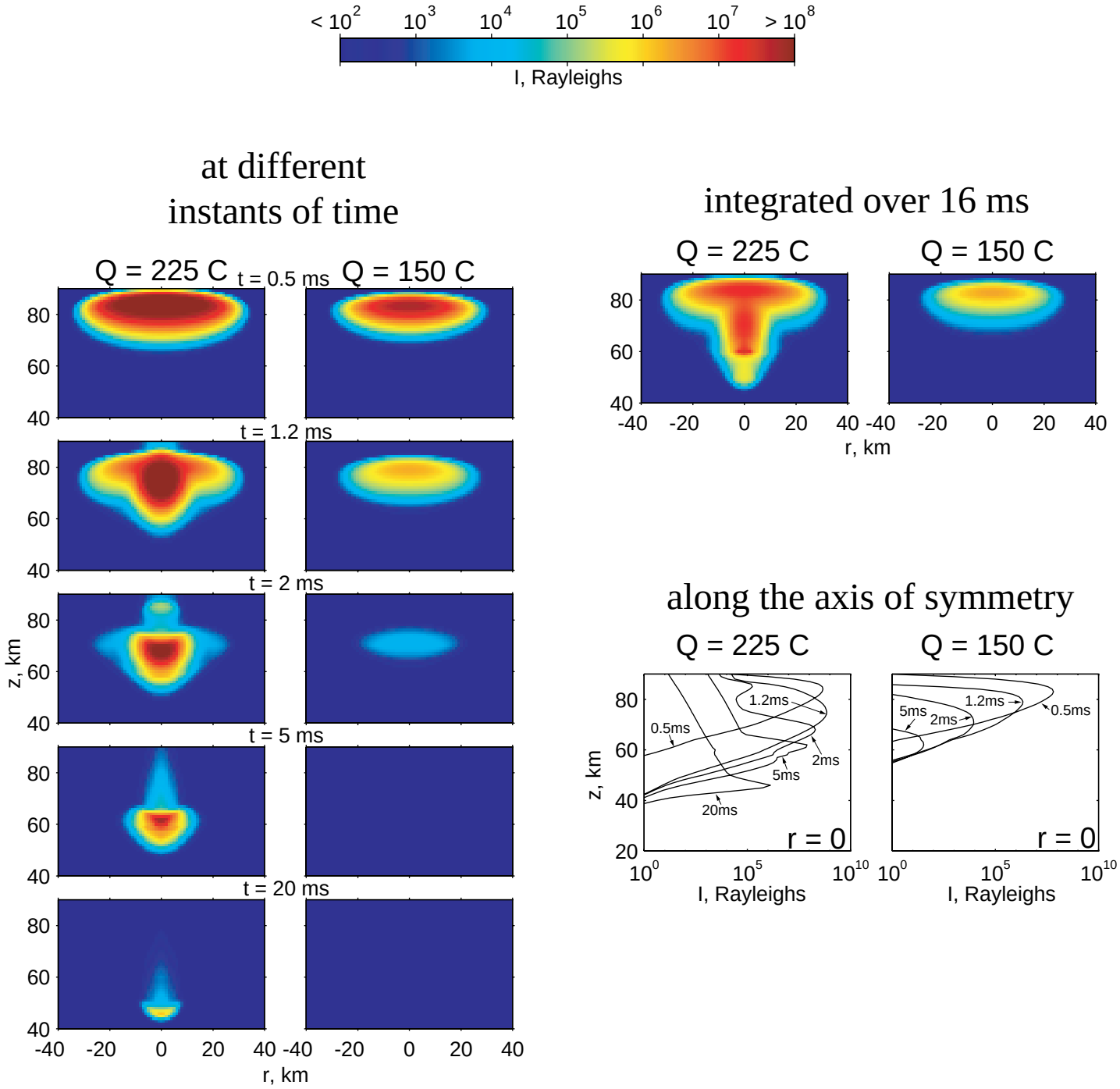
t=1.2 ms (maximum)



along the axis of symmetry

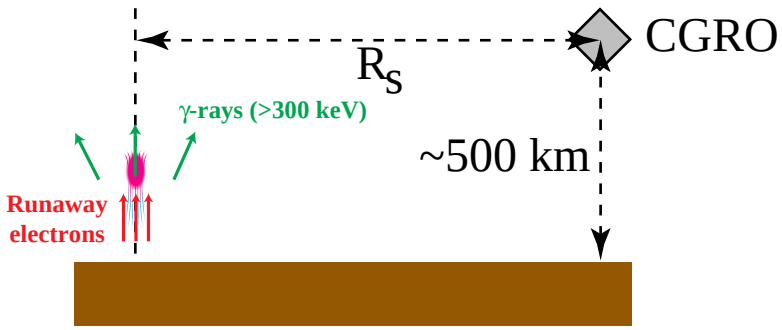


Intensity of the N_2 First Positive band, Q=225 C and Q=150 C

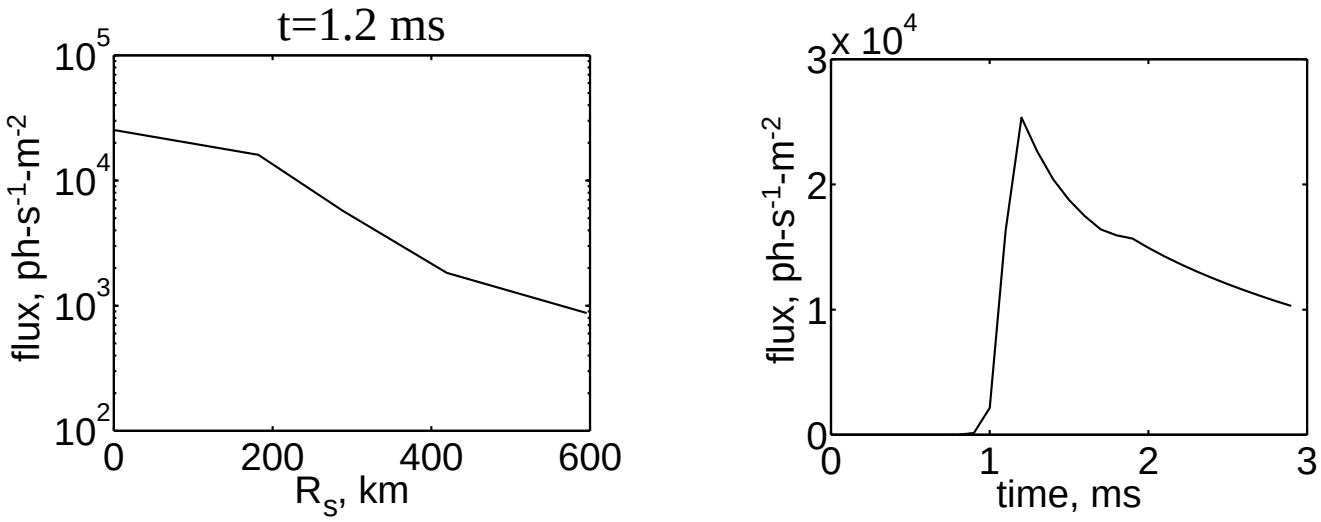


Predicted γ-ray emissions

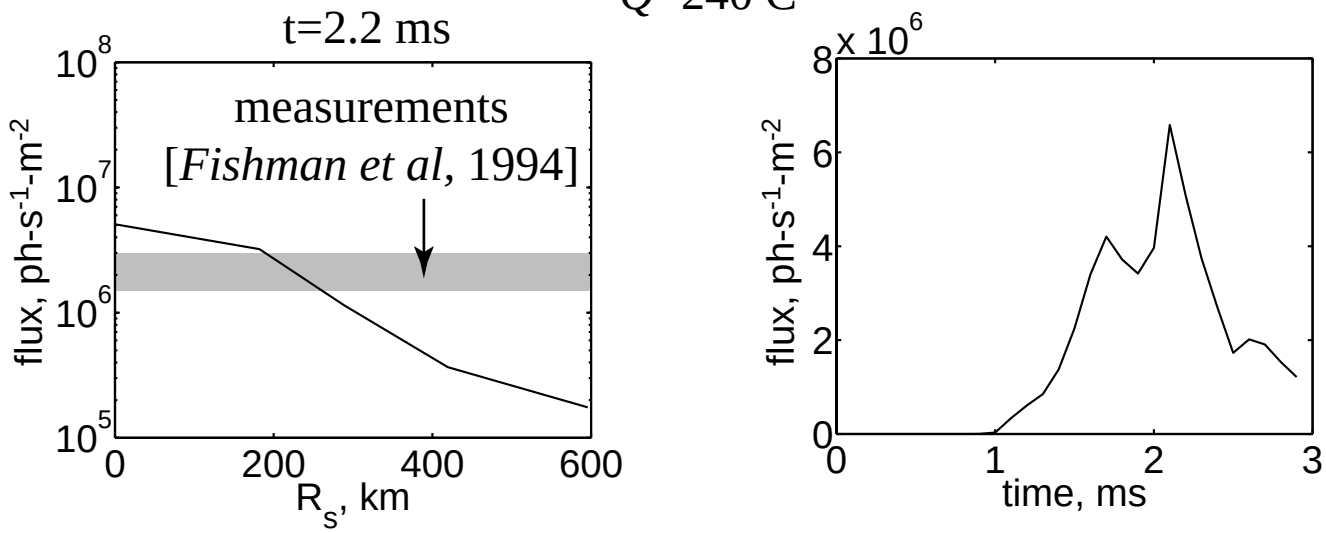
γ-ray emissions are due to bremsstrahlung by runaway electrons



Q=225 C



Q=240 C



Summary

- ¥ We calculated the flow of REL in a cylindrically symmetric system with vertical geomagnetic field, using a two-dimensional REL-QE model.

- ¥ The model self-consistently includes effects of the REL on the electric field and the conductivity of the atmosphere.

- ¥ We analized the possible contribution of REL to the optical emissions, caused by heating of free electrons by the thundercloud quasi-electrostatic field.

- ¥ It was shown that the REL-QE model, taking into account the contribution of the REL in the ionization process, gives high optical emissions at altitudes 40-60 km, in contrast to heating of ambient electrons that can explain emissions at >80 km.

- ¥ The emissions from the ionization channel created by REL closely resemble the observed shape and altitudes of the common columnar type of Sprite.

- ¥ For an exponential ambient conductivity profile we consider the REL to play a significant role only for discharges of ‡200C.

- ¥ Calculated γ-ray fluxes are in agreement with fluxes observed by the BATSE detector [*Fishman et al.*, 1994].