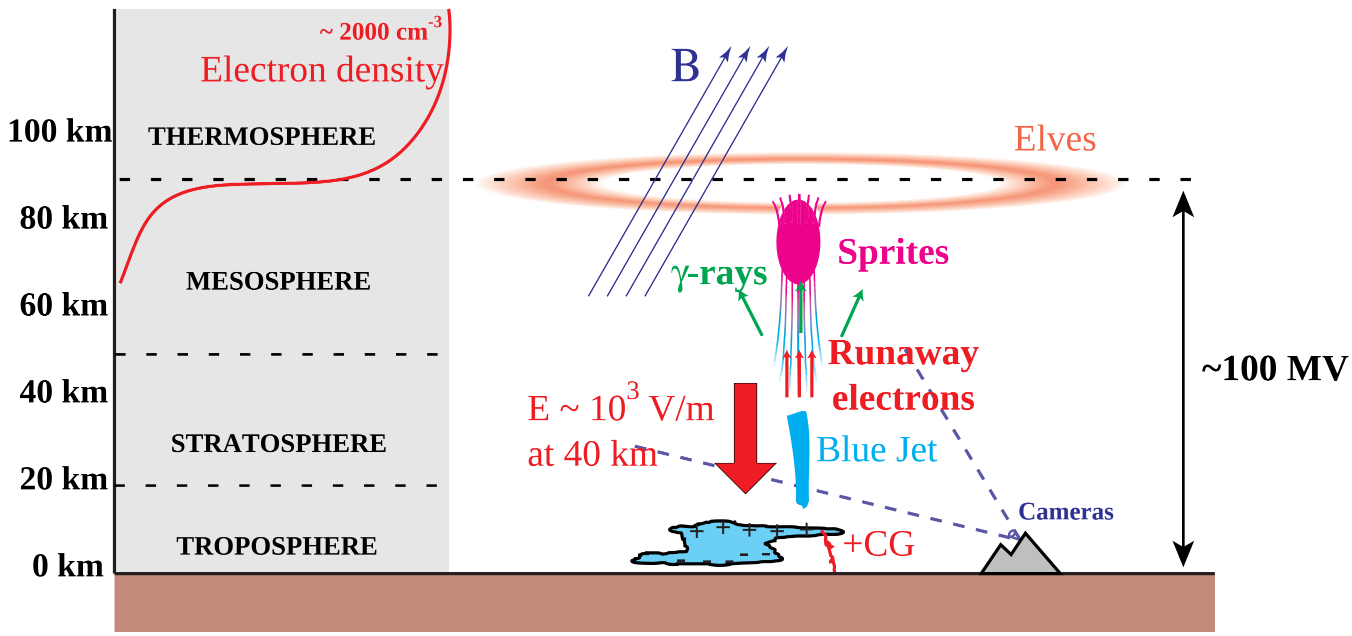
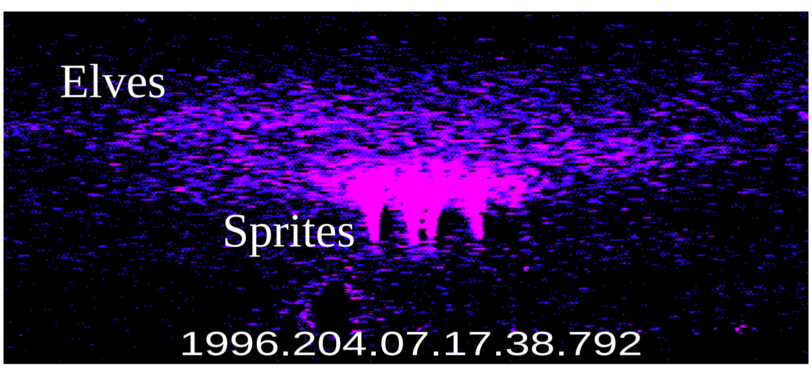
Monte Carlo Simulation of Runaway MeV Electron Breakdown with Application to Red Sprites and Terrestrial Gamma Ray Flashes

N. G. Lehtinen
(STAR Laboratory, Stanford, CA 94305)

Lightning-mesosphere interaction phenomena

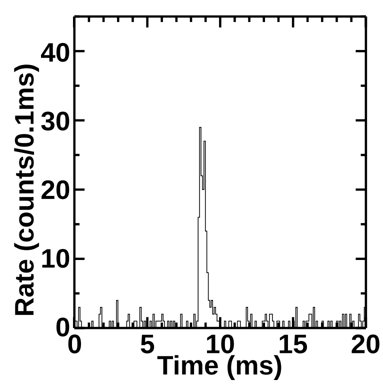


Red Sprites



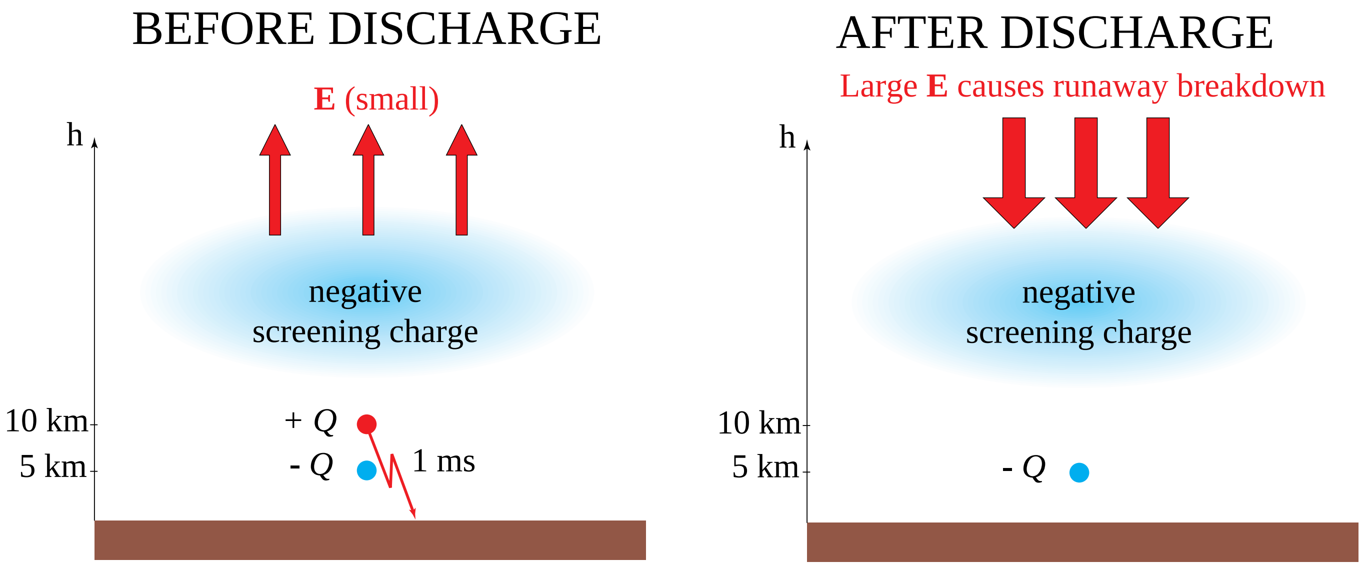
Red Sprites:
- altitude range ~50-90 km
- lateral extent ~5-10 km
- occur ~1-5 ms after +CG discharge
- last up to several 10 ms

γ-ray flash (BATSE observation)

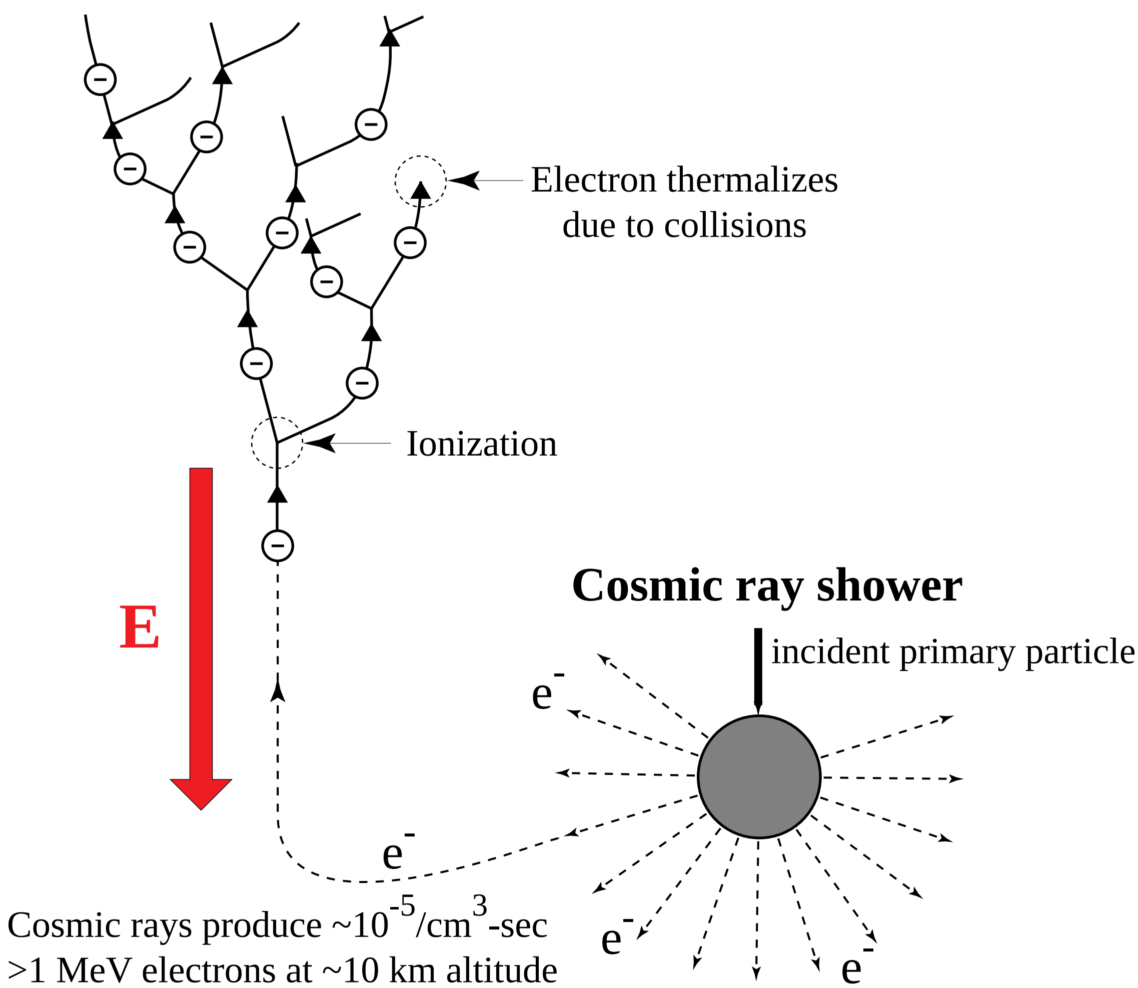


Terrestrial Gamma Rays:
- time duration ~1 ms
- energies 20 keV–2 MeV
  (shown 100–300 keV)

Production of accelerating E field



Runaway electron avalanche



Runaway electron avalanche studies

Previous runaway avalanche models:

- Analytical [*Gurevich et al.*, 1996; *Sizykh et al.*, 1993; *Bulanov et al.*, 1997]
- Kinetic [*Symbalisty et al.,* 1998]
- Monte Carlo [*Shveigert*, 1988]

Goals of runaway avalanche studies:

- Avalanche rates
- Distribution functions

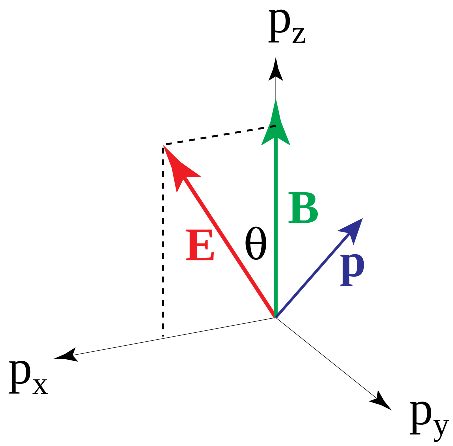
Applications:

- Atmosphere
- High energy plasmas (astrophysics, fusion)

Motivation for this work:

- The previous kinetic and Monte Carlo models do not include magnetic field
- Discrepancies between different models

Monte Carlo model



1. Relativistic equation of motion:

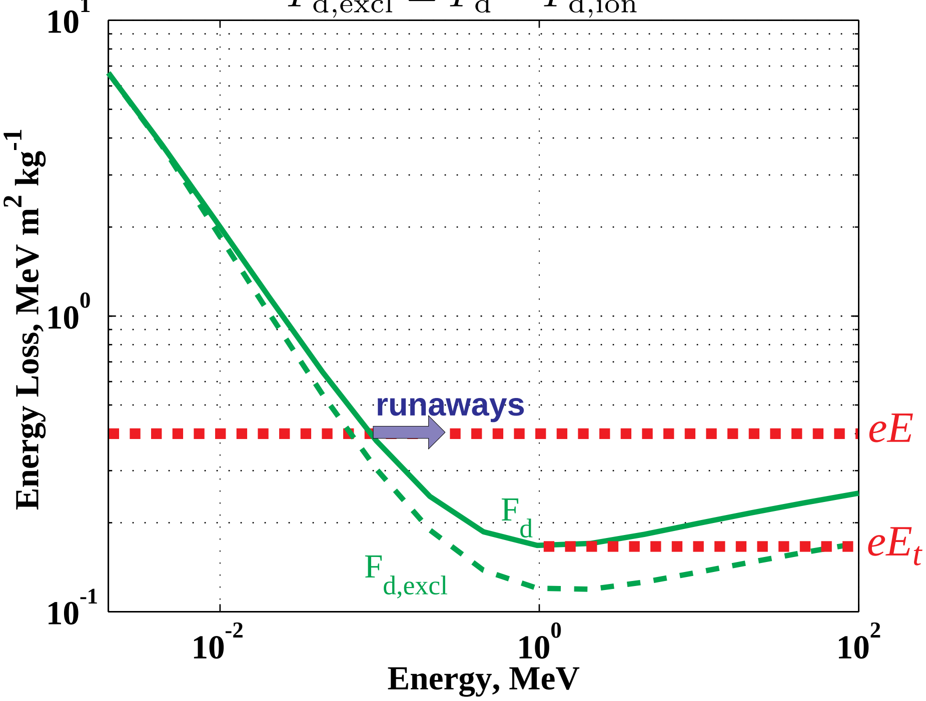
$$\frac{d\mathbf{p}}{dt} = -e\mathbf{E} - \frac{e}{m\gamma}\mathbf{p} \times \mathbf{B} + \vec{\Gamma}(t)$$

2. Production of new electrons in the ionization process.

Forces due to scattering:

$$\vec{\Gamma} = \underbrace{\mathbf{F}_{\mathrm{d,excl}}}_{\text{dynamic friction}} + \underbrace{\vec{\Gamma}_{\mathrm{ion}}}_{\text{ionization}} + \underbrace{\vec{\Gamma}_{\mathrm{el}}}_{\text{elastic scattering}}$$

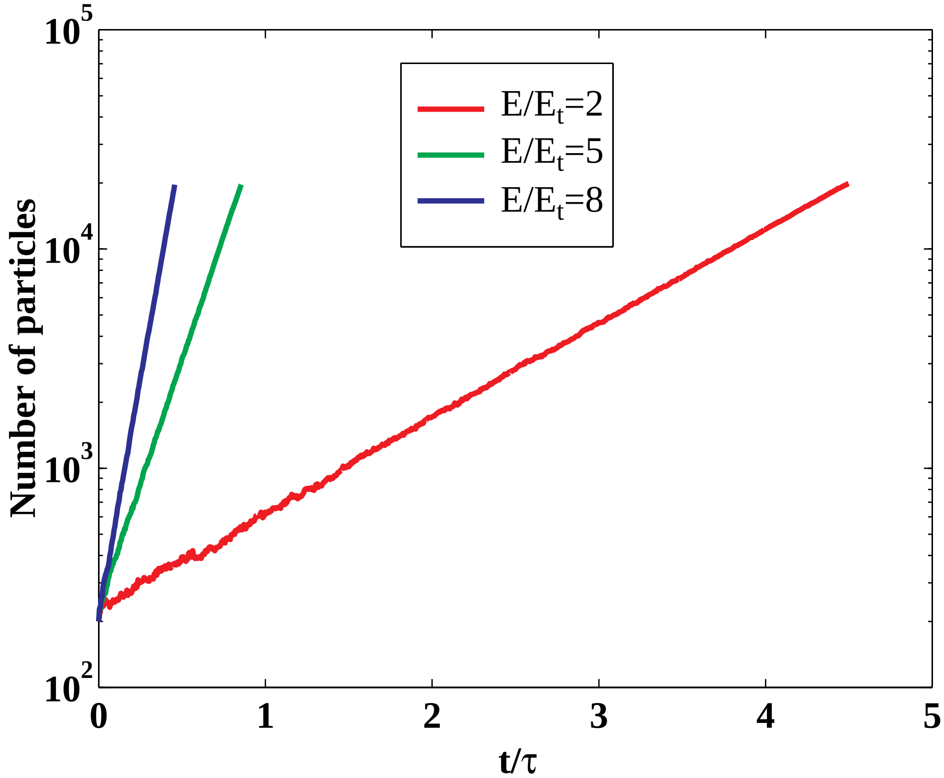
$$F_{\mathrm{d,excl}} = F_{\mathrm{d}} - F_{\mathrm{d,ion}}$$



$E_t \sim 0.1E_c$; E_c is the conventional breakdown (sparking) field

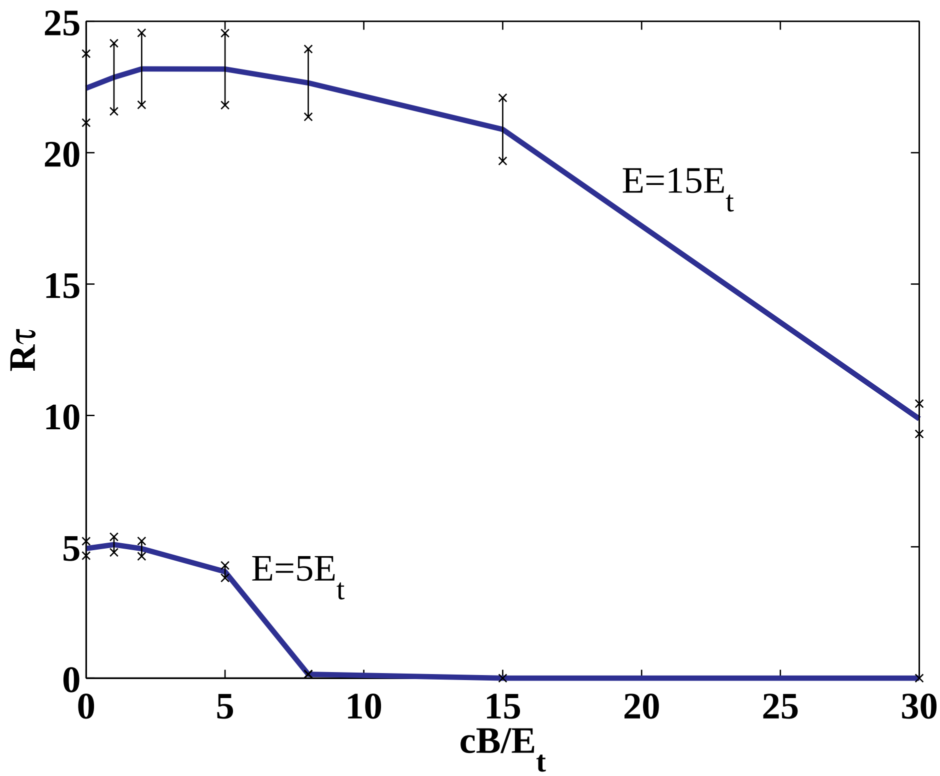
Growth of the number of particles

$$N_R(t) \sim e^{Rt}$$



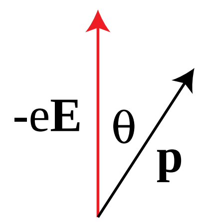
$\tau \simeq 172$ ns at sea level

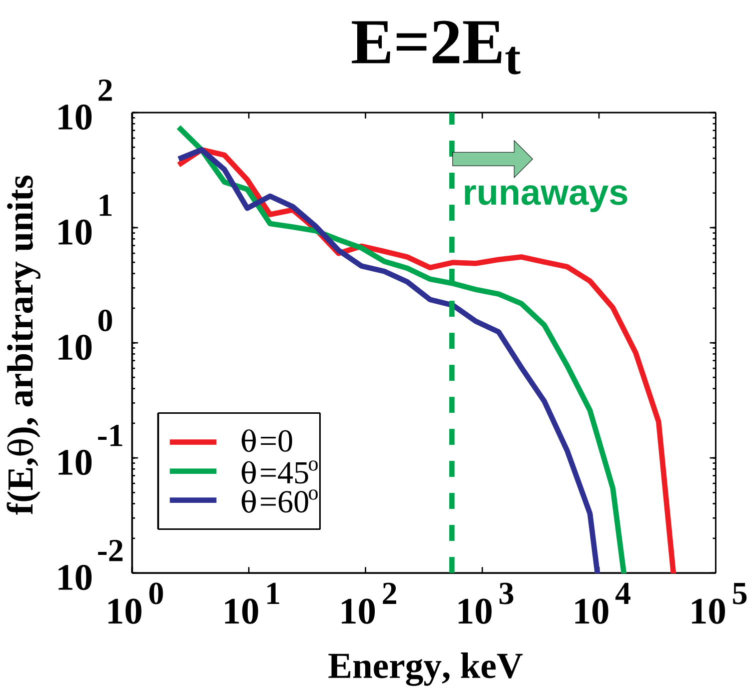
Runaway avalanche growth rate *R* (B⊥E)

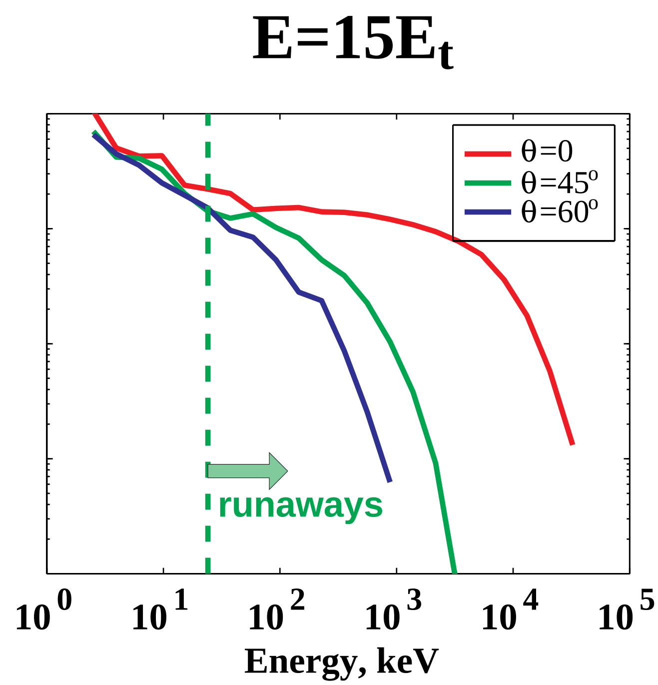


- the avalanche grows faster at higher electric fields
- these results agree for B=0 with kinetic calculations of *Symbalisty et al.* [1998] within a factor of 1.5
- high perpendicular magnetic field quenches the runaway electron avalanche

Electron distribution function (B=0)



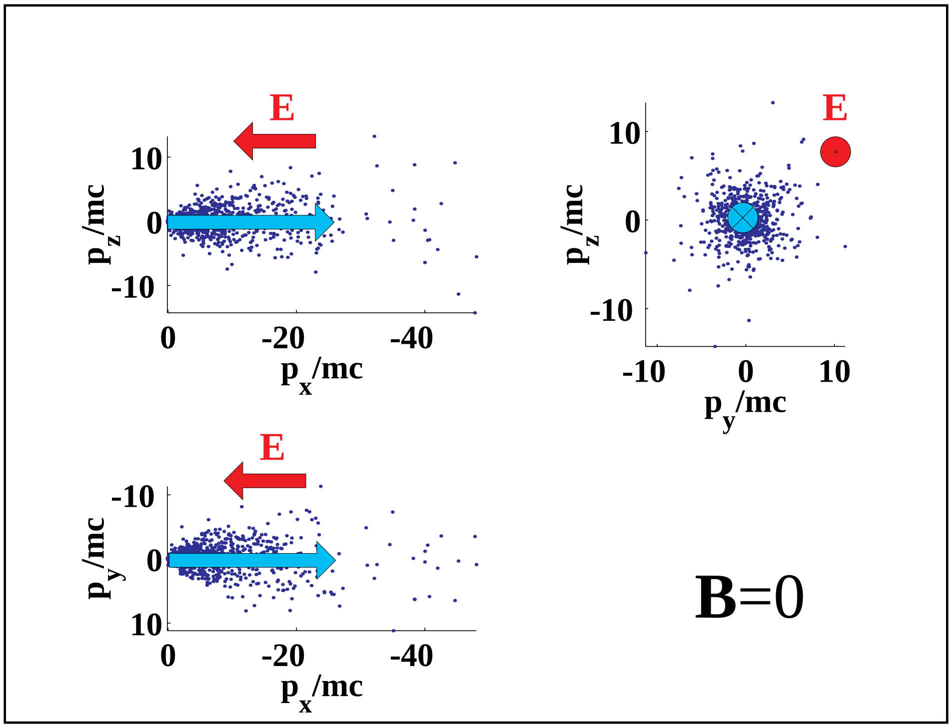


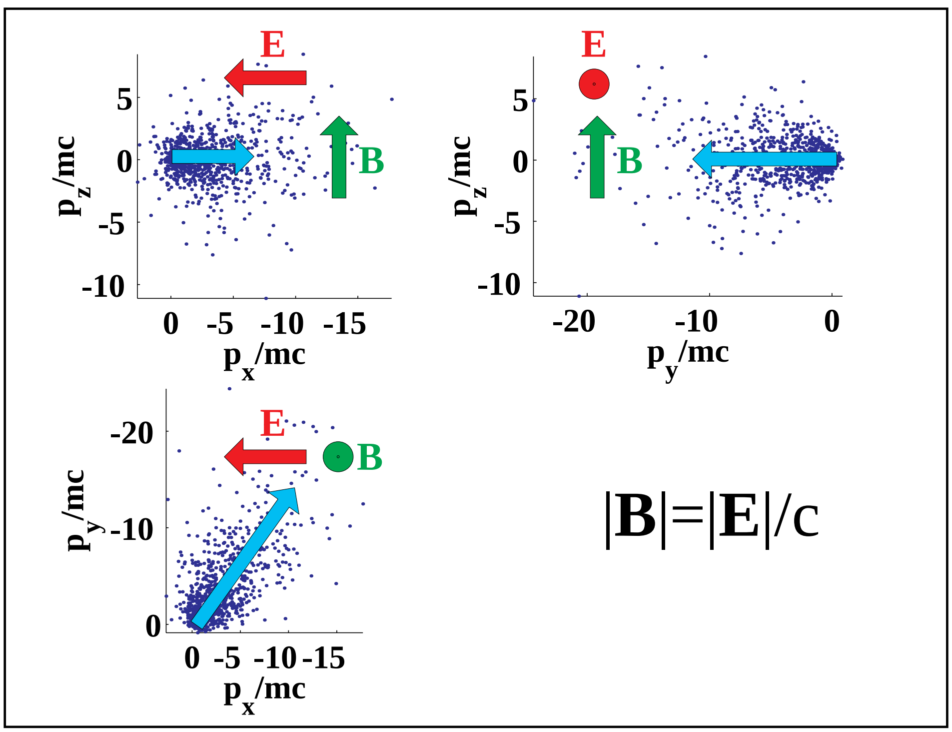


- the runaway electron beam is more bunched forward at higher electric fields

Electrons in momentum space for E⊥B

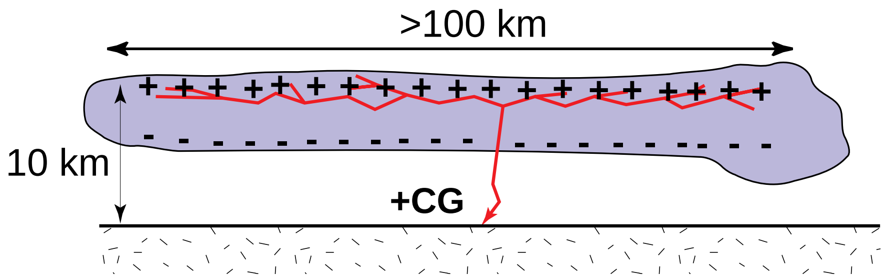
$E=5E_t$



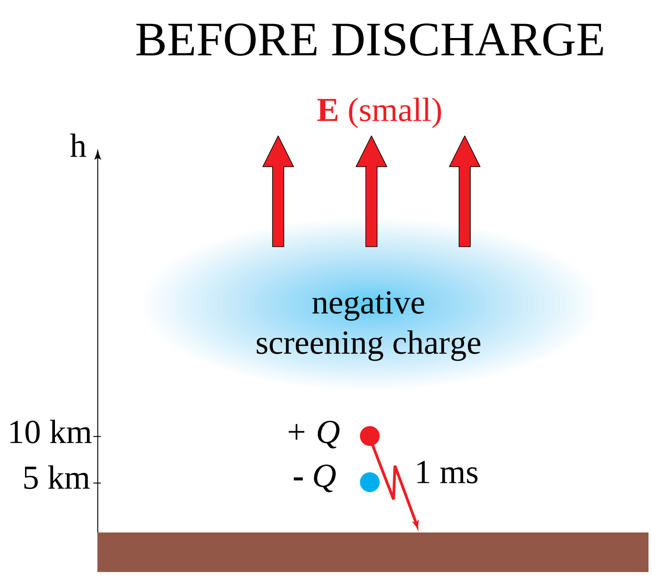


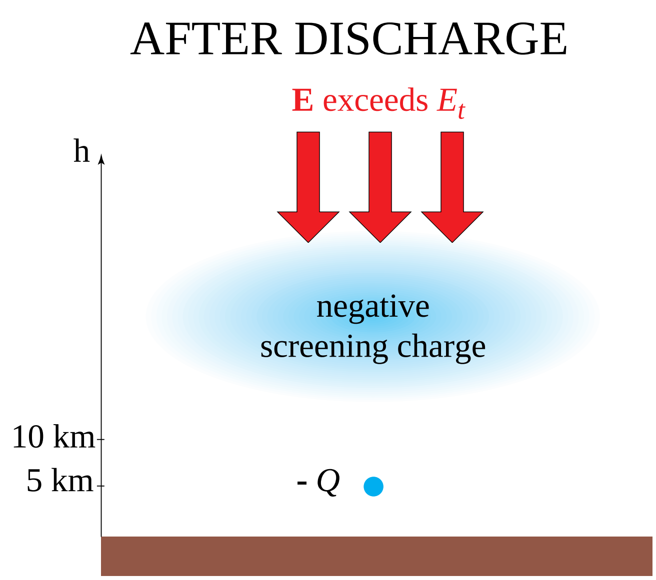
|**B**|=2|**E**|/c: No avalanche

Application to middle atmosphere



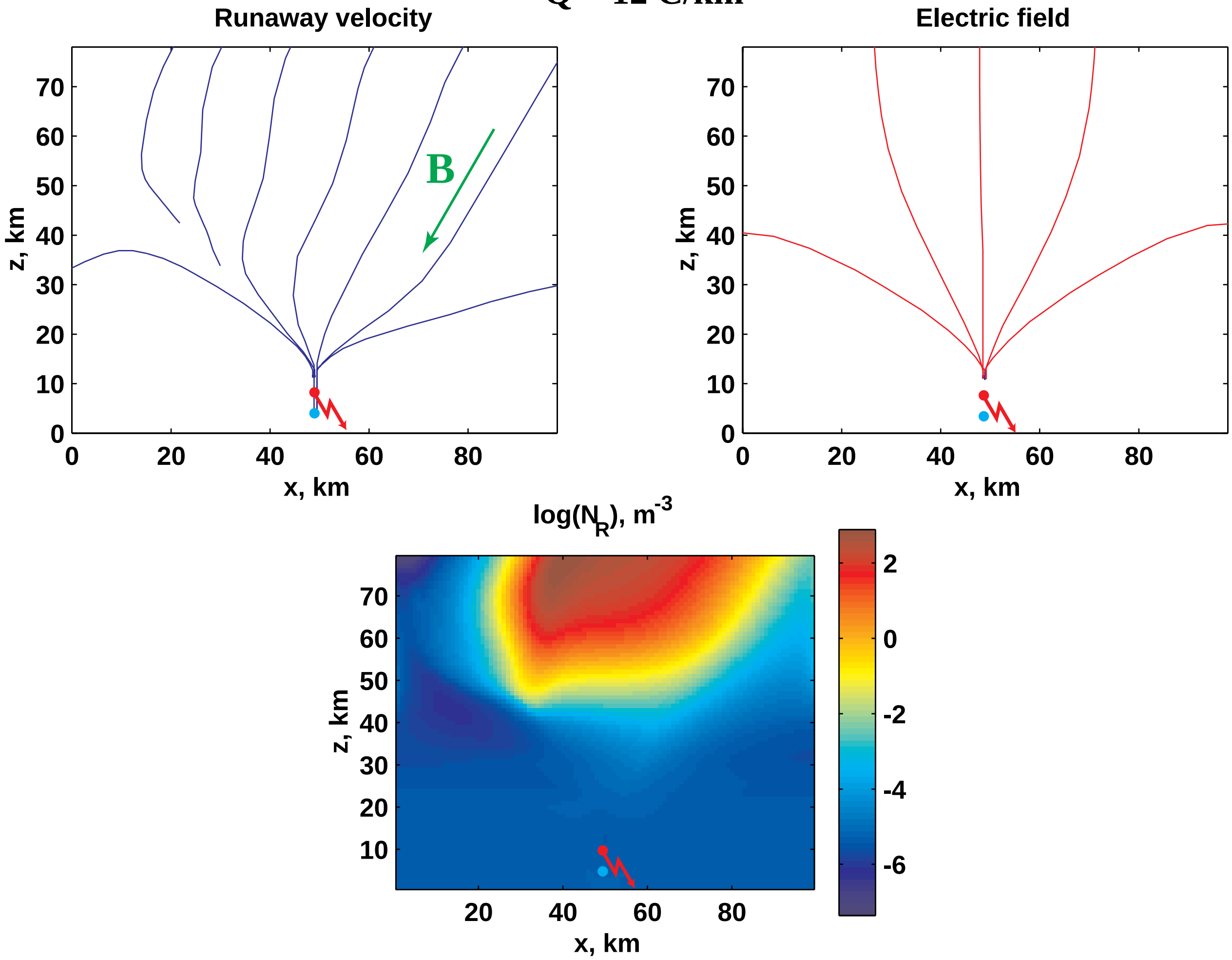
- cartesian (translationally symmetric along y axis)
- quasielectrostatic [*Pasko et al.*, 1997]
- fluid model for runaway electrons [*Lehtinen et al.*, 1997]
- use lookup table for runaway electron avalanche rates and velocities of the beam, generated by Monte Carlo model.



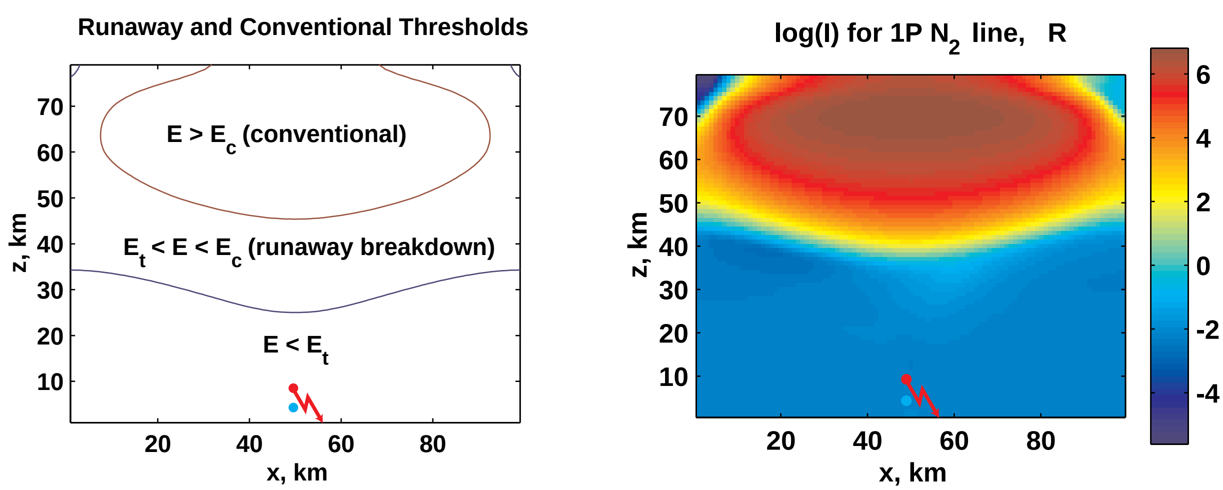


Application to Sprites

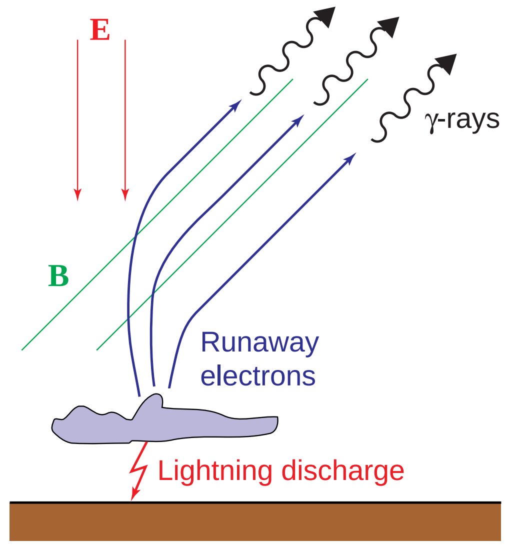
Q = 12 C/km

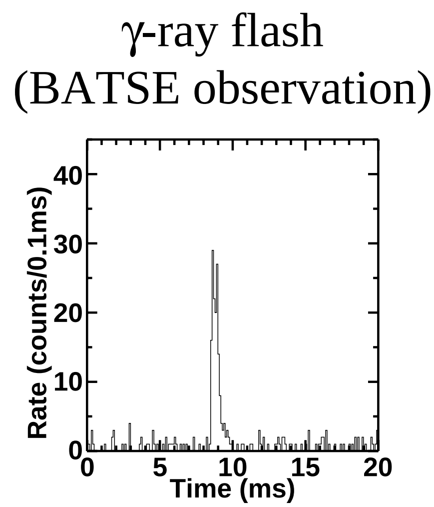


Electric field and optical emissions

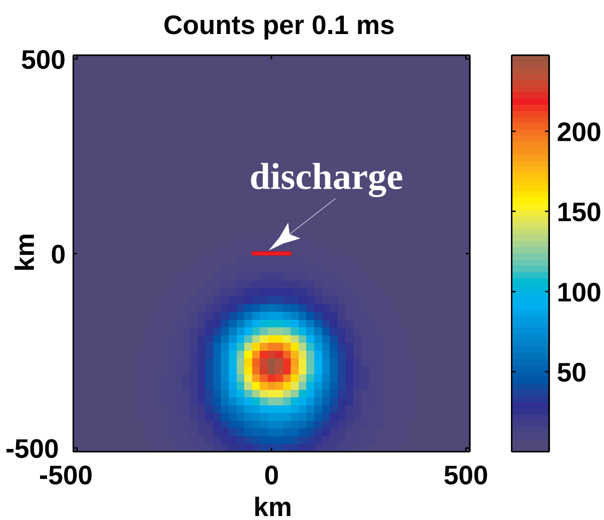


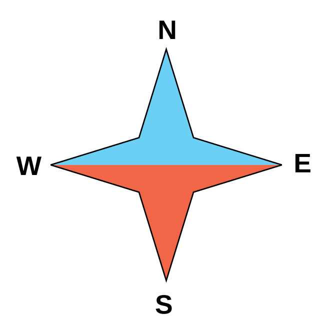
Terrestrial Gamma Ray Flashes





Simulated BATSE data at ~45° magnetic north latitude 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.

- The optical emissions associated with relativistic electrons are small compared to conventional breakdown emissions.

- For sufficiently large discharge values, the runaway electron-produced γ-rays flux values agree with BATSE data [*Fishman et al.*, 1994].