In the present work, we calculate the distribution function and avalanche rates of energetic REL in air in the presence of static electric and magnetic fields using a Monte Carlo simulation in three dimensions, and compare the results to previous kinetic and analytical models (e.g., 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; Roussel-Dupré, R. A., A. V. Gurevich, T. Tunnel and G. M. Milikh, Kinetic theory of runaway breakdown, Phys. Rev., 49, 2257, 1994). These results are applied to REL beams in the upper atmosphere, as the post-discharge quasi-electrostatic field above thunderstorms following a positive lightning stroke can be large enough to cause an avalanche of runaway electrons (REL). We consider the case of lightning draining positive charge from remote regions of a laterally extensive (> 100 km) thundercloud. In this case we use a cartesian coordinate model which is translationally symmetric with respect to the direction of the extended thundercloud. In contrast to the previously reported cylindrically symmetric 2D model, this model allows for an arbitrary dip angle of the geomagnetic field, and may better describe discharges at mid-latitudes, associated with Red Sprites.
Lightning-mesosphere interaction phenomena

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 $\gamma$-ray flashes:
- last ~1 ms
- were correlated with thunderstorms

[Inan et al., 1996]
Runaway Electron Avalanche

Ionization process is described by Moller cross-section

Electron thermalizes due to dynamic friction

Cosmic ray shower

\[ S_0 \sim 10^{-5} / \text{cm}^3 \cdot \text{sec} \]

at \( \sim 10 \) km altitude

(\( >1 \) MeV electrons)
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:

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

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 \(\Gamma(t)\):

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

Exclude losses to created electrons from the friction:

\[F_{d,excl}(p) = F_d(p) - N_m Z_m \int_{\varepsilon - \varepsilon_{min}}^{\varepsilon_{min} \Delta \varepsilon} \sigma(\varepsilon, \varepsilon') d\varepsilon'\]
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:

   \[
   \frac{1}{\tau_i} = \frac{\partial N_R/\partial t}{N_R} = \frac{\int_{\text{producers}} \text{REL} N_m v \sigma_{\text{tot}} f(\vec{p}) d^3 \vec{p}}{\int_{\text{REL}} f(\vec{p}) d^3 \vec{p}}
   \]
Electrons in momentum space for orthogonal $E$ and $B$

$E = 5E_t$

**No magn. field**

**B=E/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]

PRODUCTION OF GAMMA RAYS
2D structure of runaway electron density and optical emissions in the First Positive Band of N$_2$

$\lambda = 8$ C/km, $t = 3$ms after discharge, B lies in (x,z) plane

Simulated BATSE data at ~45° magnetic N latituudte in $\gamma$-ray 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, *personal communication*.


