Runaway Air Breakdown in the Context of High-Altitude Discharges

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Abstract

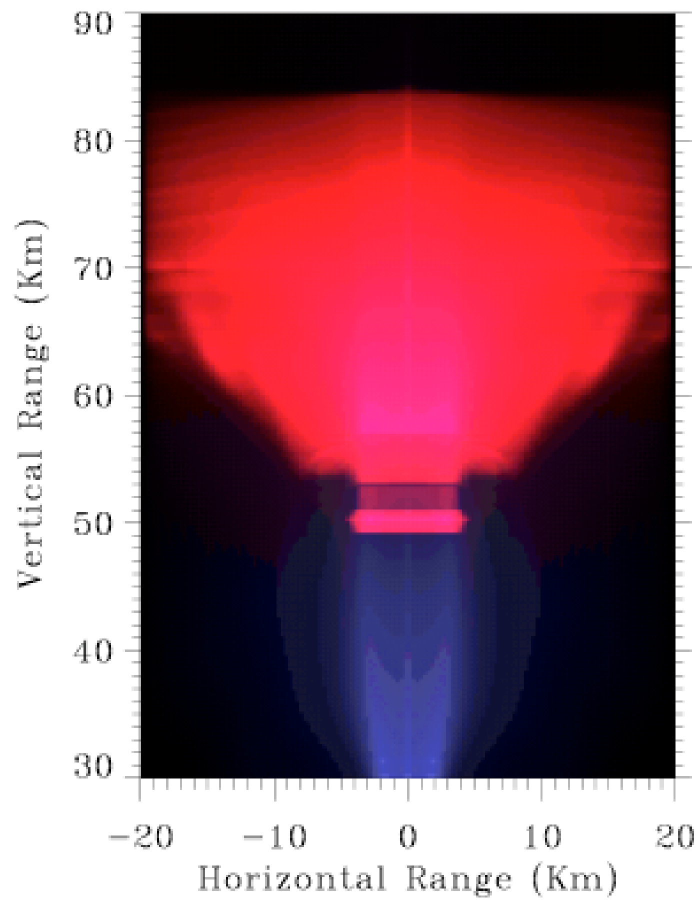
The fundamental physical processes inherent to the relativistic breakdown mechanism known as runaway breakdown are reviewed. The kinetic theory is described and the most recent calculations for the electron distribution function and the associated avalanche rates are presented. Given the kinetic results it is possible to develop a set of fluid equations which when coupled to Maxwell's equations governs the evolution of a discharge driven by external electric fields such as the quasi-electrostatic fields generated in a high-altitude discharge. The results of 2-D, fully electromagnetic simulations of transient luminous events initiated by positive lightning discharges are presented. Details of the electron density and electric field evolution and the gamma ray flux expected at a satellite borne sensor are discussed.

Outline

- Review of Runaway Breakdown
- Comparison of Runaway and Conventional Breakdown
- Simulations of Sprites
- TGF Calculations vs. RHESSI Measurements
- Summary

Sprite Simulation

(200 C in 1 ms)



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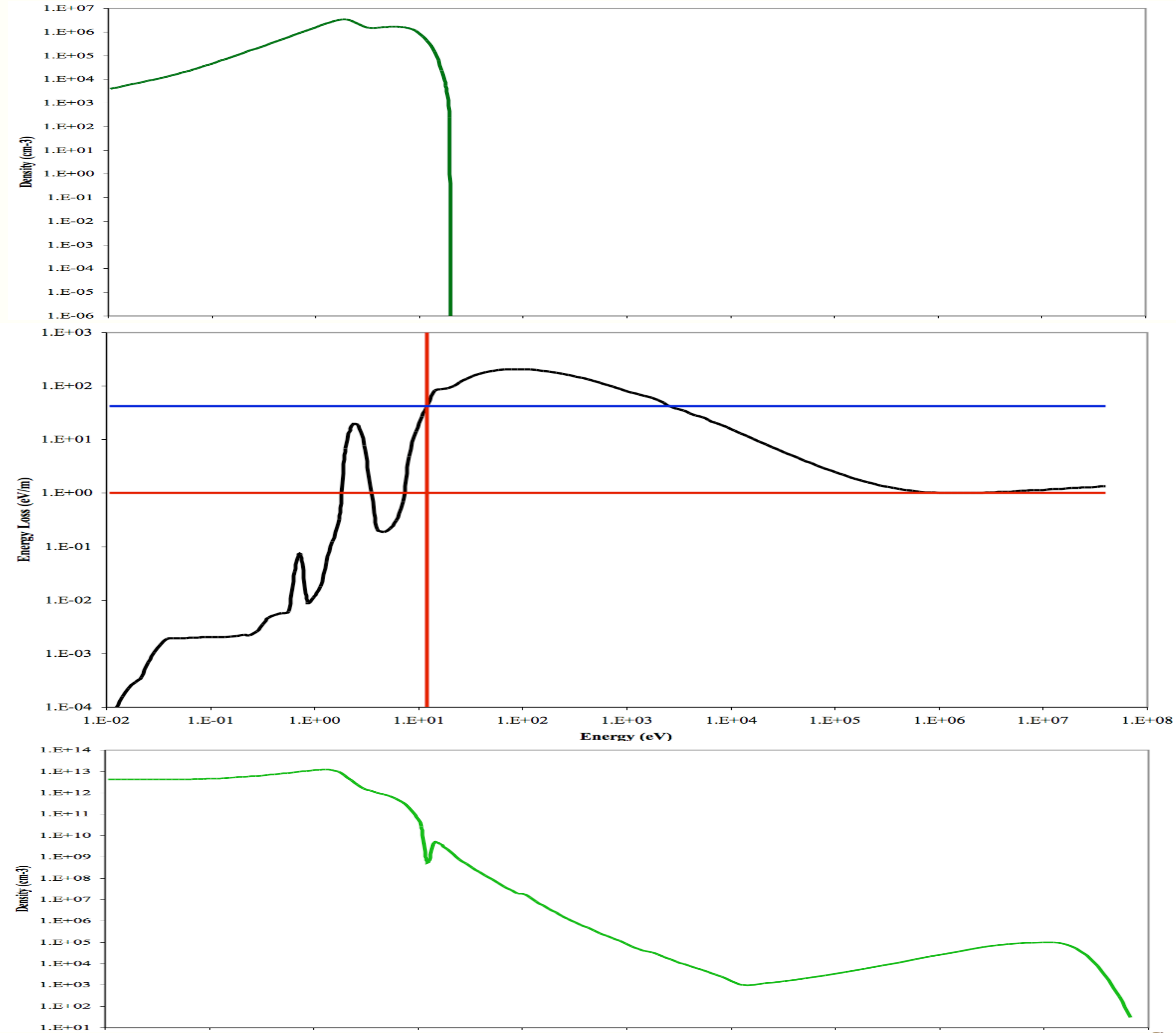
RB - Mechanism (Gurevich et al., 1992)



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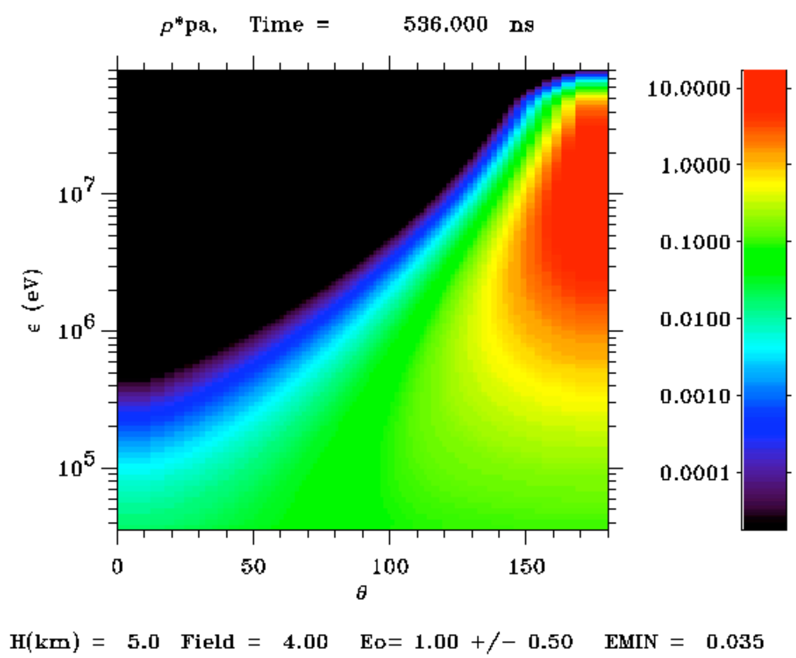
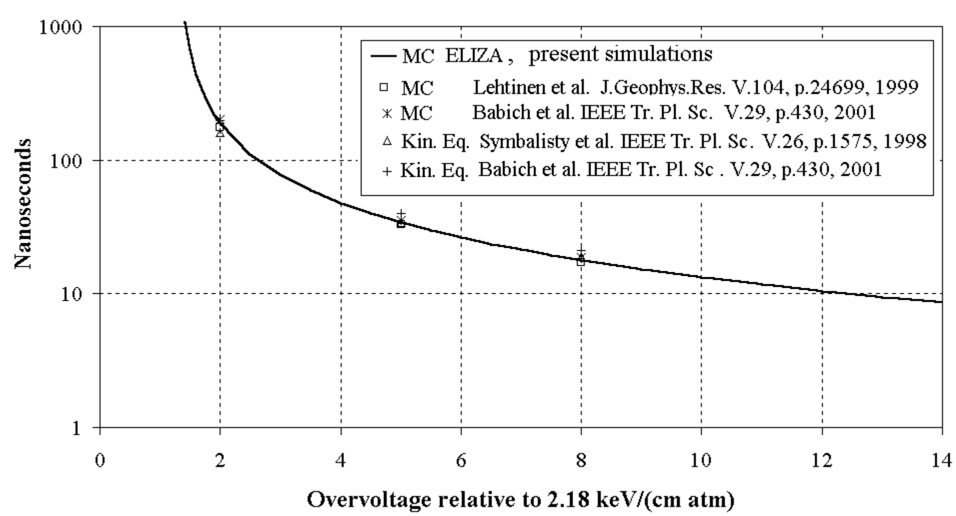
RB - Electron Distribution

Electron Distribution Function

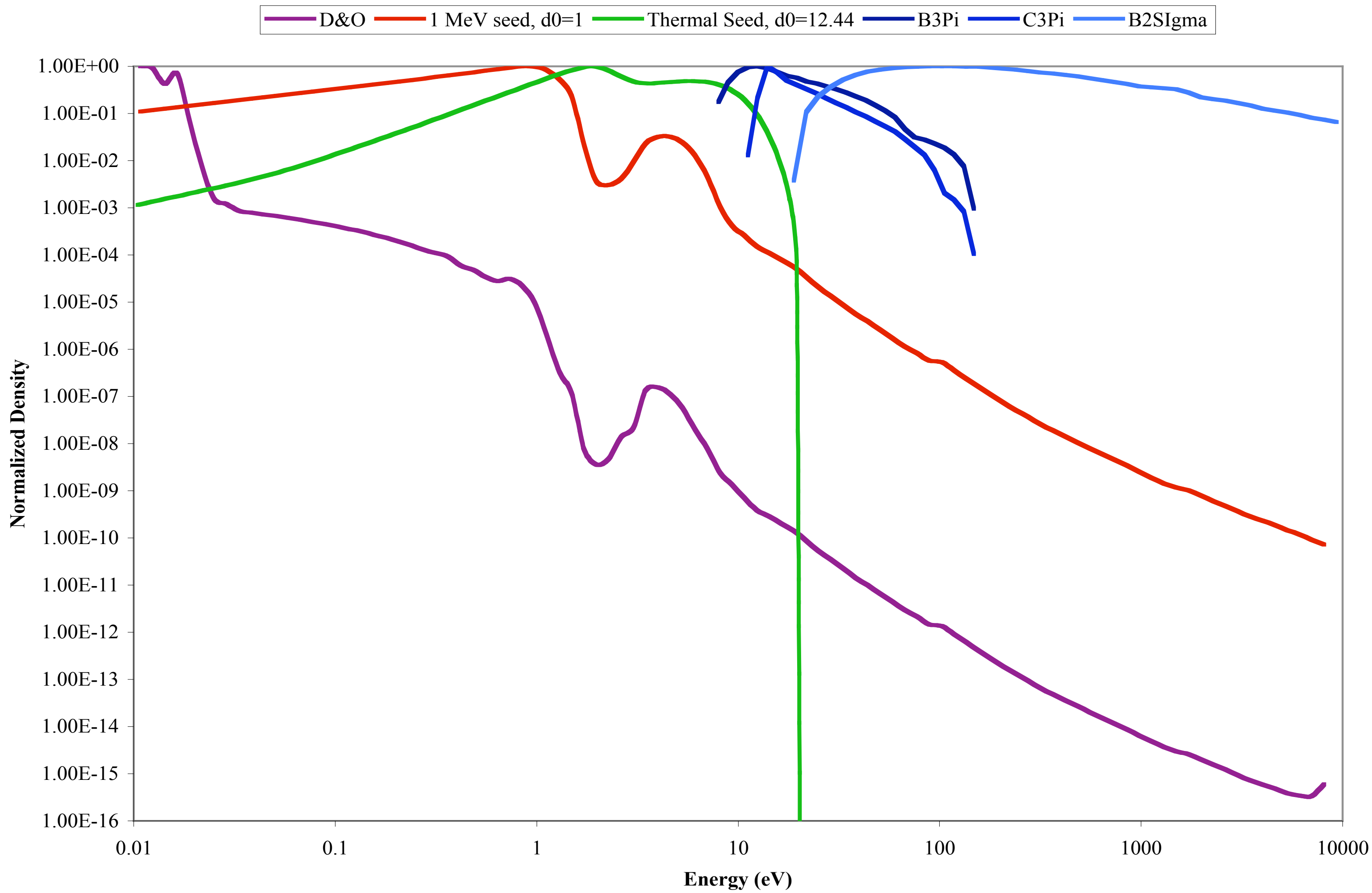
$\delta_0 = 4$



Avalanche Time Scale



RB vs Conventional



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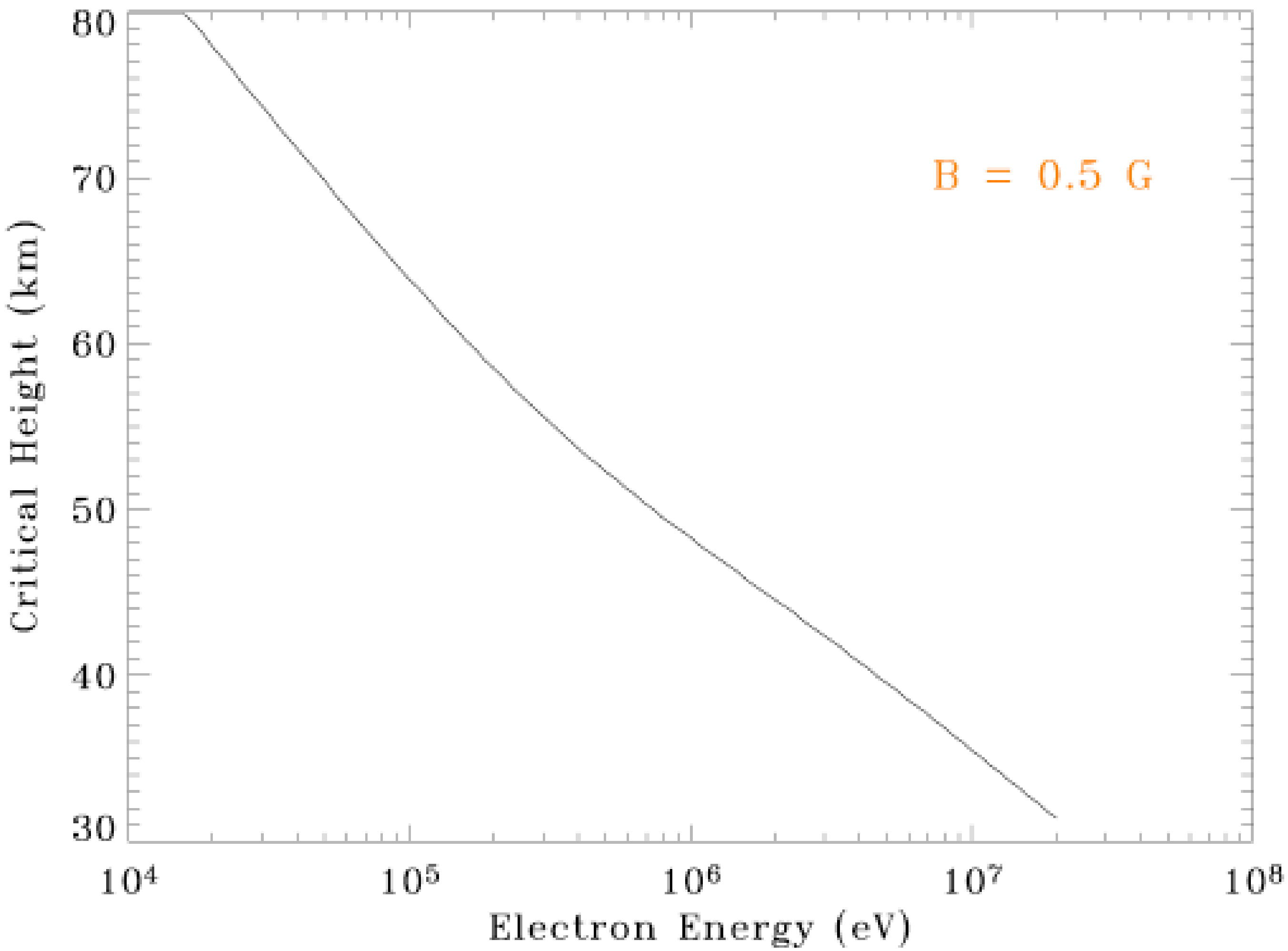
Magnetization of Runaway Electrons



Model of High-Altitude Discharges

- 2-D hydrodynamic model (cylindrical symmetry)
  - Primary/secondary electrons, negative/positive ions
  - Avalanche of runaway electrons (based on kinetic calculations)
  - Ionization, recombination, attachment
  - Full relativistic momentum equation for primary electrons
  - Swarm model for secondary electrons
  - Below runaway threshold, primaries are lost due to friction
  - Above threshold primaries sustained according to kinetic calculations at constant energy of ~ 7.2 MeV
- Simultaneous solution of 2-D Maxwell's equations
  - Fully electromagnetic
  - Currents obtained from hydro equations

Cloud Electrical Model

- Negative charge injected at a specified altitude with double exponential time profile and with a spatially diverging current density
- Spherical and pancake charge distributions are generated
- Cloud electrical conductivity assumed negligible
- Ground conductivity is modeled and taken to be 0.002 mhos/m
- Atmospheric conductivity profile taken from Hale measurements
- Simulation parameters include
  - Total charge, volume & shape of positive and negative charge layers, time scale for exponential charge build-up, ground conductivity, & initial density of charged species, and ambient air conductivity

Sprite Simulations

⇒ Negative charge injected at a specified altitude with double exponential time profile (simulates +CG lightning discharge)

⇒ Nighttime electrical conductivity measured by Hale

⇒ Simulation parameters include:

- Total charge ⇒ 200-400 C
- Shape of negative charge layer ⇒ ellipse at 8 km altitude
- Size of negative charge layer ⇒ 6 km in diameter and 1 km thick
- time scale for exponential charge build-up ⇒ 1 ms (case 1) and 8 ms (case 3)
- Grid resolution ⇒ 300 x 300 meters
- Grid size ⇒ 0-90 km altitude, 0-36 km radius

Comments (Slides 7-9)

⇒ **In our model a high-altitude discharge/sprite is initiated by first producing a simulated positive cloud-to-ground discharge or parent lightning event. We accomplish the latter by introducing negative charge into the cloud over a distributed spatial volume and within a certain period of time. In addition we reduce the field inside a specified volume (defined to be the cloud and chosen to lie between 5 and 10 km altitude) in order to prevent a discharge from developing inside the cloud in our simulations. The value chosen for the cloud top is consistent with that expected for the stratiform region of a mesoscale convective system. Note that the fields everywhere within the computational volume were taken to be zero at t = 0. In each of the simulations presented here (Cases 1 and 3) we deposited 200 C of charge at an altitude of 8 km over an ellipsoid with a maximum radial diameter of 6 km and a maximum thickness of 1 km. The time to build up the charge was set to 8 ms and 1 ms for Cases 3 and 1, respectively. A slow continuing current existed in the simulations after these nominal time scales. The computational grid included 120 radial cells from 0–36 km and 300 vertical cells extending from 0-90 km altitude. The spatial resolution was 300 x 300 m. The ambient atmospheric conductivity was taken from the measurements of Hale. The quasi-static electric field that develops at high-altitudes (outside of the cloud volume mentioned above) as a result of the parent lightning serves to drive the discharge that is ultimately manifested as a sprite or TLE.**

Equation Set

Fluid Equations

$$\frac{\partial n_p}{\partial t} = -\nabla \cdot n_p \mathbf{v}_p + R_p n_p + F_c / \lambda_{mfp}$$

$$\frac{\partial \mathbf{S}}{\partial t} = -\nabla \cdot \mathbf{S}\, \mathbf{v}_p - e n_p \left(\mathbf{E} + \mathbf{v}_p \times \mathbf{B} \right) - \upsilon\, \mathbf{S} + R_p\, \mathbf{S}_0 \quad \text{where,} \quad \mathbf{S} = \gamma\, n_p \mathbf{v}_p\,, \quad \mathbf{S}_0 = \gamma\, n_p v_0\, \mathbf{E}/|\mathrm{E}|$$

$$\frac{\partial n_s}{\partial t} = -\nabla \cdot n_s \mathbf{v}_s + R_s n_p - \alpha\, n_s + \nu_i n_s - \alpha_R n_+ n_s$$

$$\frac{\partial n_-}{\partial t} = -\nabla \cdot n_- \mathbf{v}_- + \alpha n_s - \alpha_I n_+ n_-$$

$$\frac{\partial n_+}{\partial t} = -\nabla \cdot n_+ \mathbf{v}_+ + R_s n_p + R_p n_p + \nu_i n_s - \alpha_I n_+ n_- - \alpha_R n_+ n_s$$

Maxwell's Equations

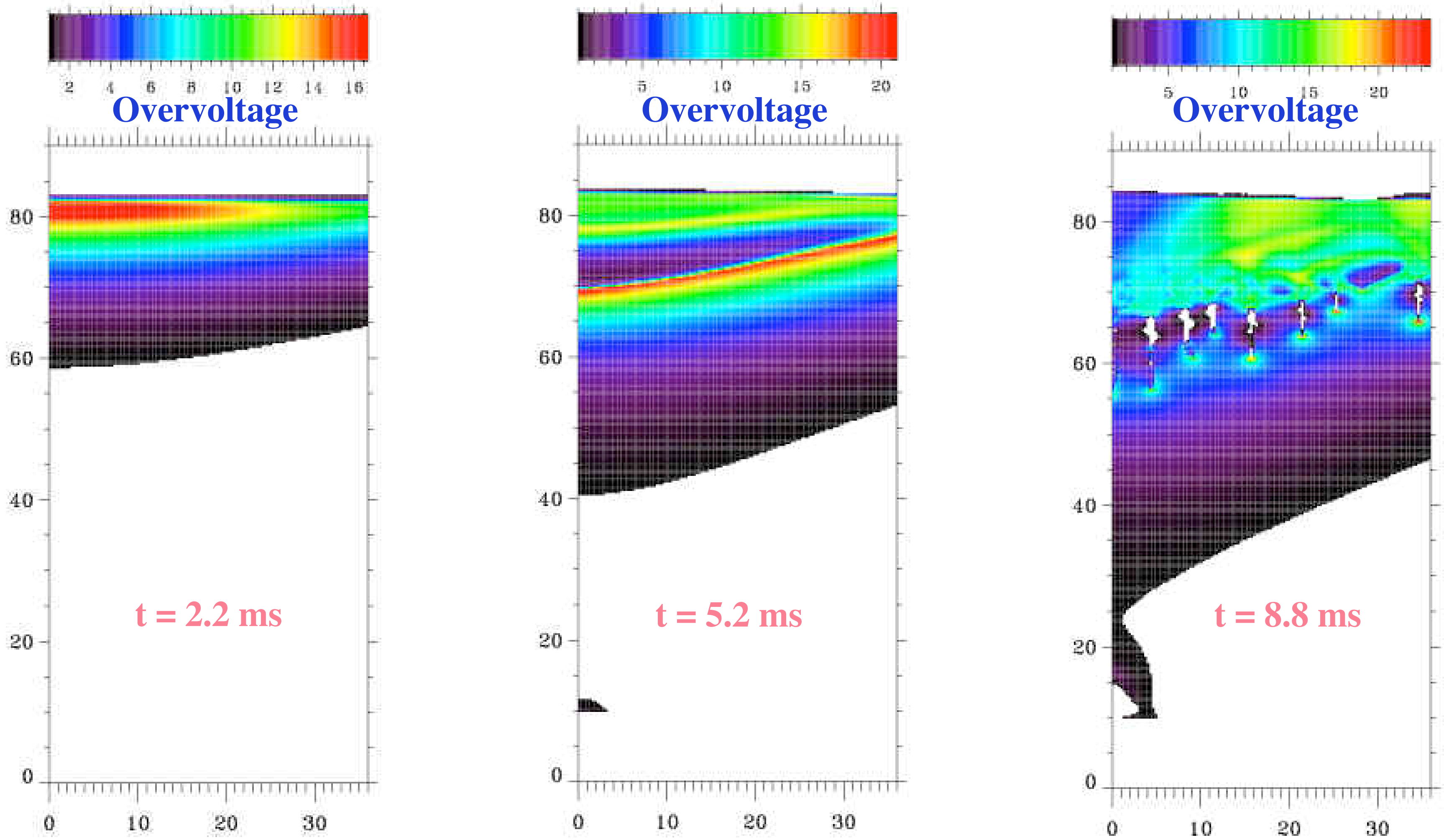
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \quad \frac{\partial \mathbf{D}}{\partial t} = \nabla \times \mathbf{H} - \mathbf{J}, \quad \mathbf{B} = \mu\, \mathbf{H}, \quad \mathbf{D} = \varepsilon\, \mathbf{E}, \quad \mathbf{J} = \sigma\, \mathbf{E} + \mathbf{J}_p + \mathbf{J}_{Lightning}$$

Comments (Slide 11)

⇒ **We evolve in time the secondary and primary electron populations (n_s, n_p), and the positive and negative ion populations (n_+,n_-). We do not currently independently solve for the secondary electron momenta (or velocity) and energy. For the ions, we use the mobility to find the ion velocities. For the secondary, or slow, electrons we compute their velocity (V_s) from fits to swarm data. For the primary, or relativistic, electrons we compute their velocity (V_p) from a momentum equation and their energy (ε_p) from the Boltzmann equation solutions for the avalanche process. The source and sink terms for various particle species include $R_{p,}$ the avalanche rate of runaway electrons, F_c, the flux of cosmic-ray produced primary electrons, R_s = R_p, the production rate of secondary electrons by means of primary ionization, ε_i = 34 eV is the energy loss per ion pair produced in air, ν, the primary electron scattering rate, ν_i, the avalanche rate for low-energy electrons (ionization minus dissociative attachment), α, the three-body attachment rate, α_R, the radiative recombination rate, and $\alpha_{I,}$ the ion-ion recombination rate, λ_{mfp} is the primary electron mean free path, γ is the Lorentz factor for the primary electron, and V_+ and V_- are the positive and negative ion velocities, respectively.**

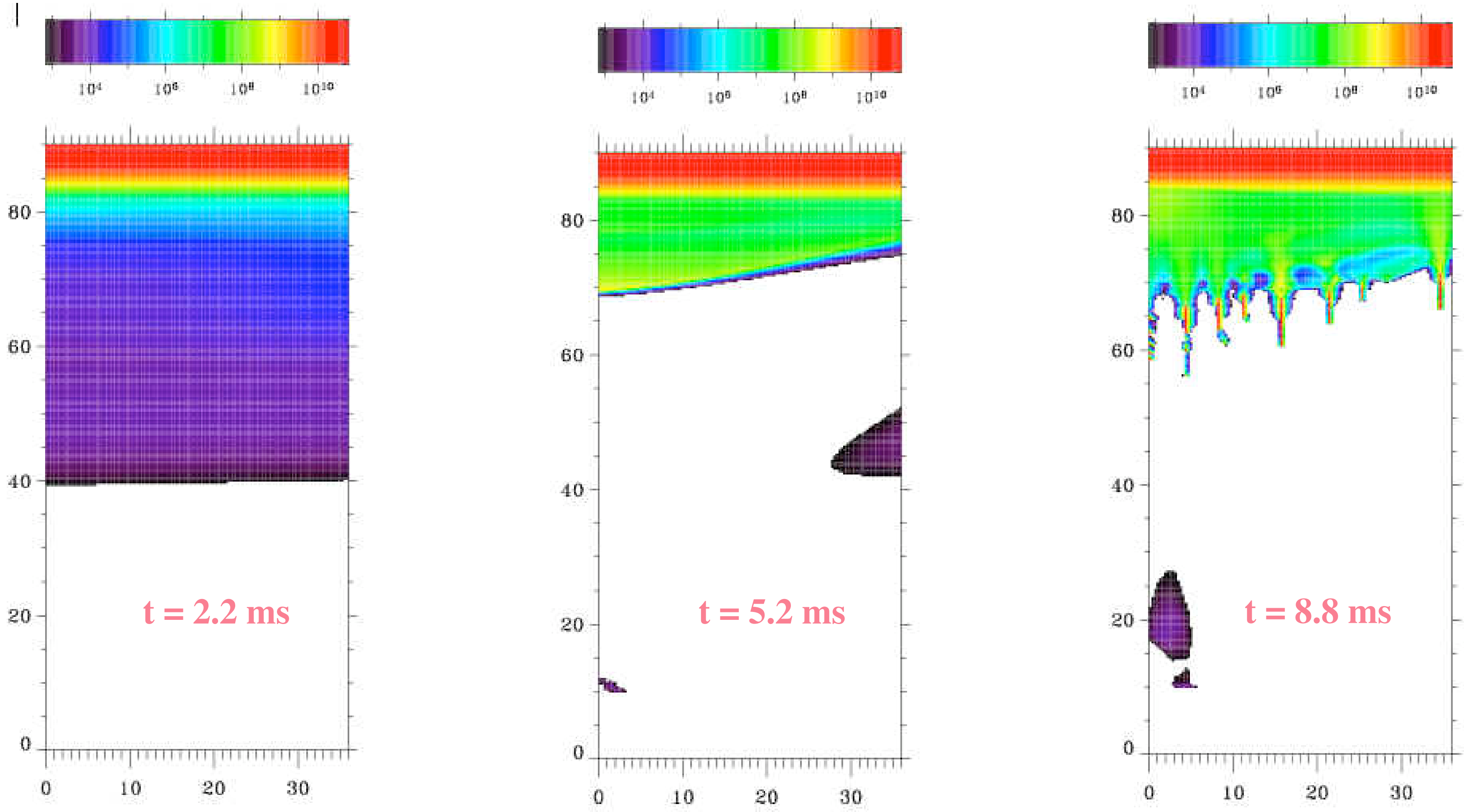
Field Configuration & Evolution

Sprite Simulation (Case 3)



Secondary Electron Density (m^{-3})

Sprite Simulation (Case 3)



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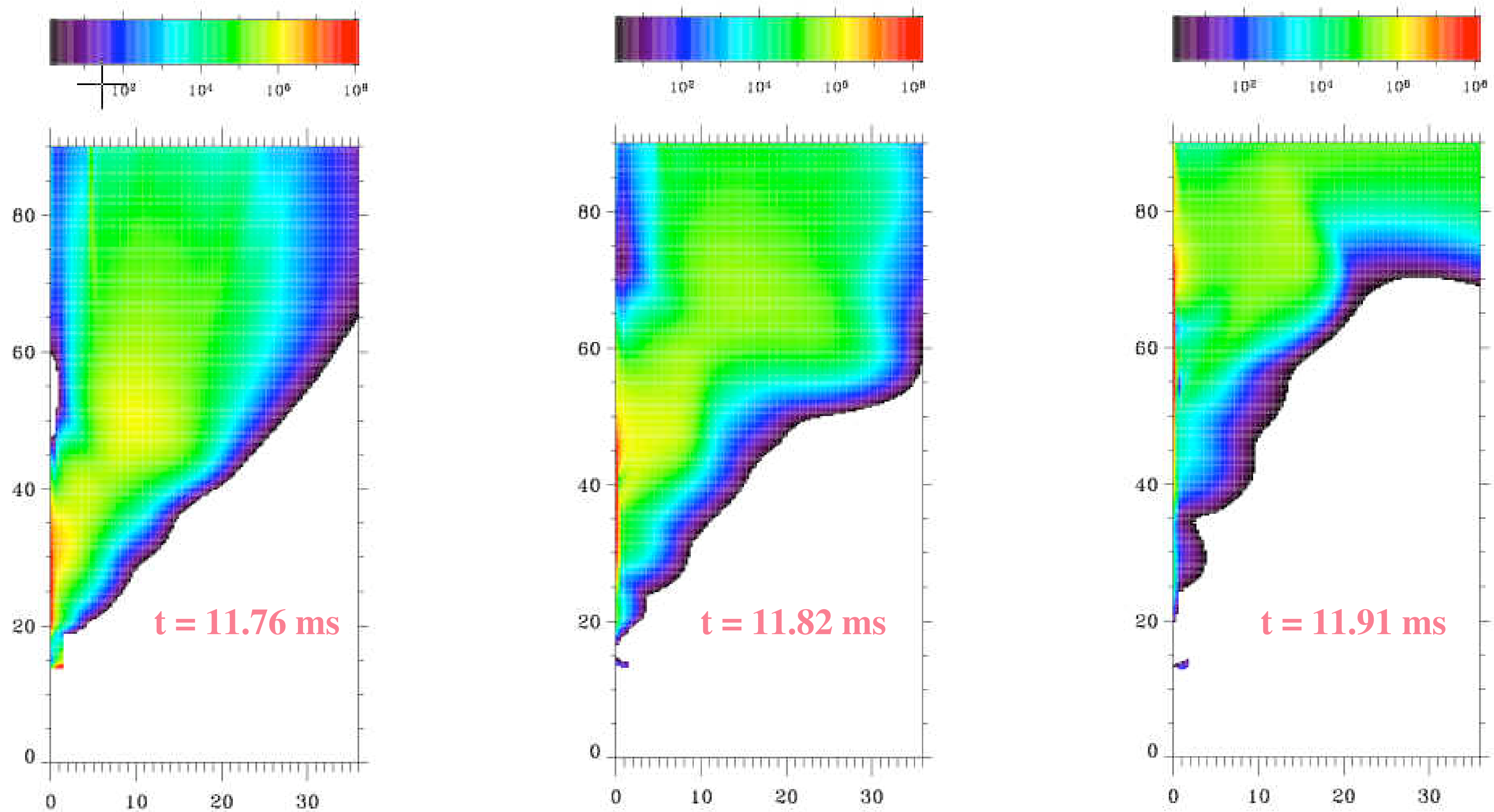
Primary Electron Densities (m^{-3})

Sprite Simulation (Case 3)



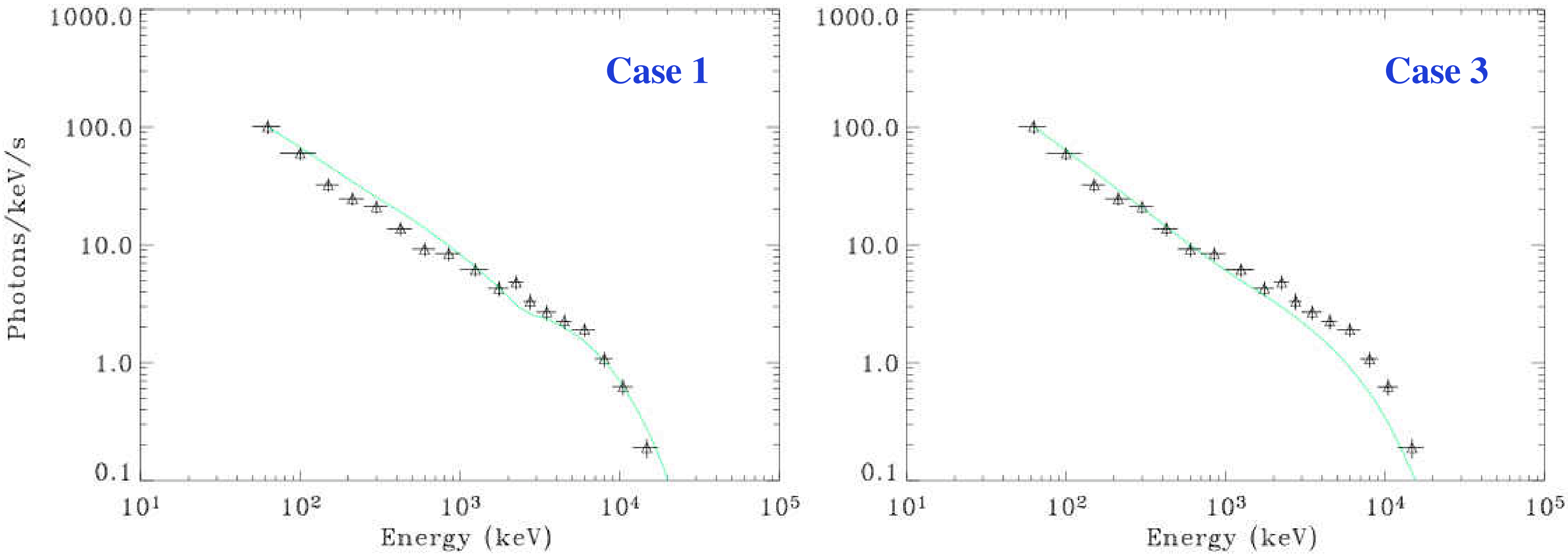
RHESSI Measurements

D.M. Smith, L.I. Lopez, R.P. Lin, C.P. Barrington-Leigh

- Reuven Ramaty High Energy Solar Spectroscopic Imager
  - NASA small explorer designed to measure X-rays and γ-rays from solar flares
  - 38^0 inclination at 600 km altitude
- Nine 7.1 cm diameter, 8.5 cm thick, germanium detectors
- Spectral range from 20 keV to 18 MeV with a few keV resolution
- Each photon arrival tagged to 1 μs
- Three months of data analyzed to yield 44 TGFs
- Measured 10x rate of BATSE events
- Event durations from 0.2 - 3.5 ms

Theory vs. Measurement

Relative Amplitudes



Runaway Breakdown is the source of TGFs

TGFs probably originate from high-altitude discharges

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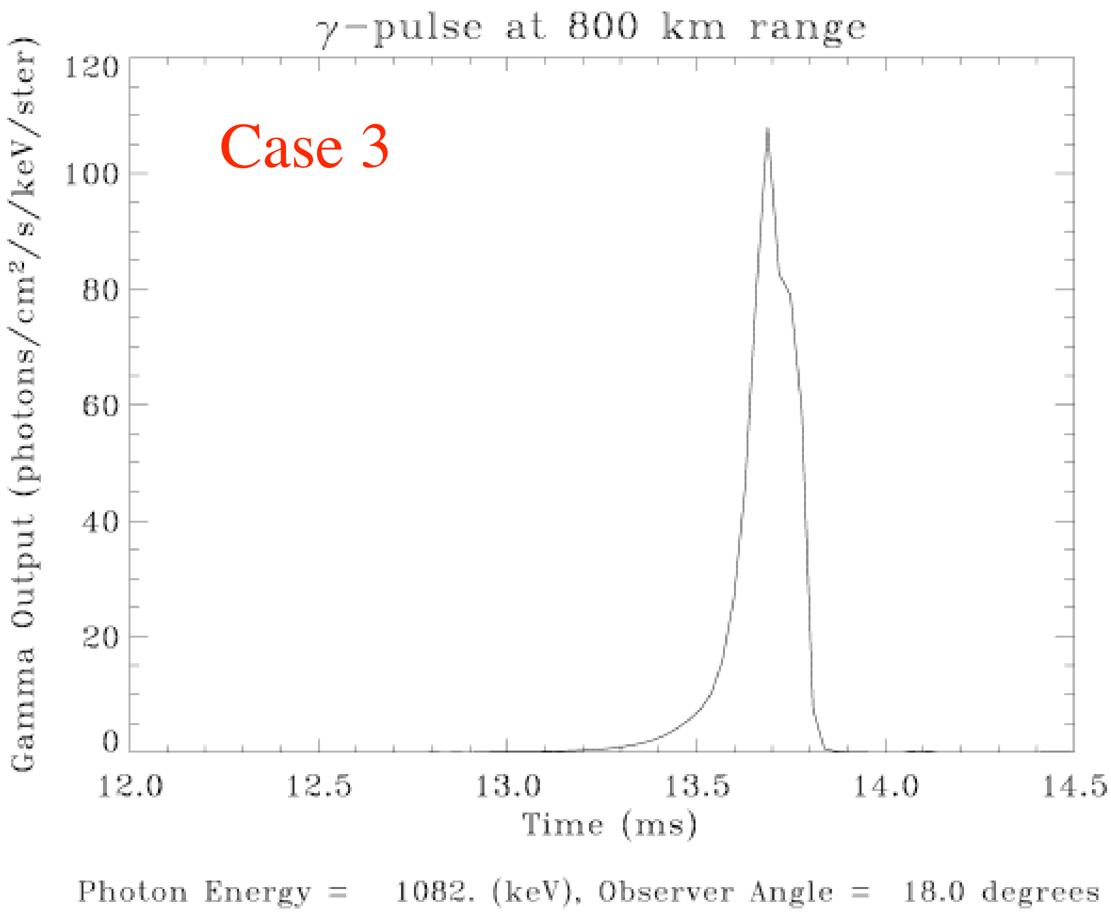
Simulated TGF Pulse



Runaway Contribution to Sprites

- Gamma ray bursts
  - TGFs are produced by runaway breakdown and undoubtedly associated with sprites
- Optical emissions
  - Spatially broad air glow
  - Impulsive photometer measurements
  - Impulsive blooming of sprites
  - Spectral measurements indicate a 1 eV population of electrons
- ELF pulse from sprites

Summary

- **Basic Theory of Runaway is Understood**
  - **More work is needed to study the combined effects of a self-magnetic field and the geomagnetic field**
  - **Runaway in non-uniform electric and magnetic fields needs further work**
  - **Effect of feedback (Dwyer) has not been studied**
  - **Electron beam stability analysis**
- **High-Altitude Discharge Simulations**
  - **3-D fully electromagnetic fluid simulations**
  - **Ultimately requires 6-D fully electromagnetic kinetic simulations**
- **Comparisons to Data**
  - **TGFs, Optical, ELF, Particle Measurements (?)**
- **Further Studies of Atmospheric Effects**
  - **Ozone, NOx, radiation belts, conjugate optical events, infrasound(??)**