Gamma-ray events from thunderclouds

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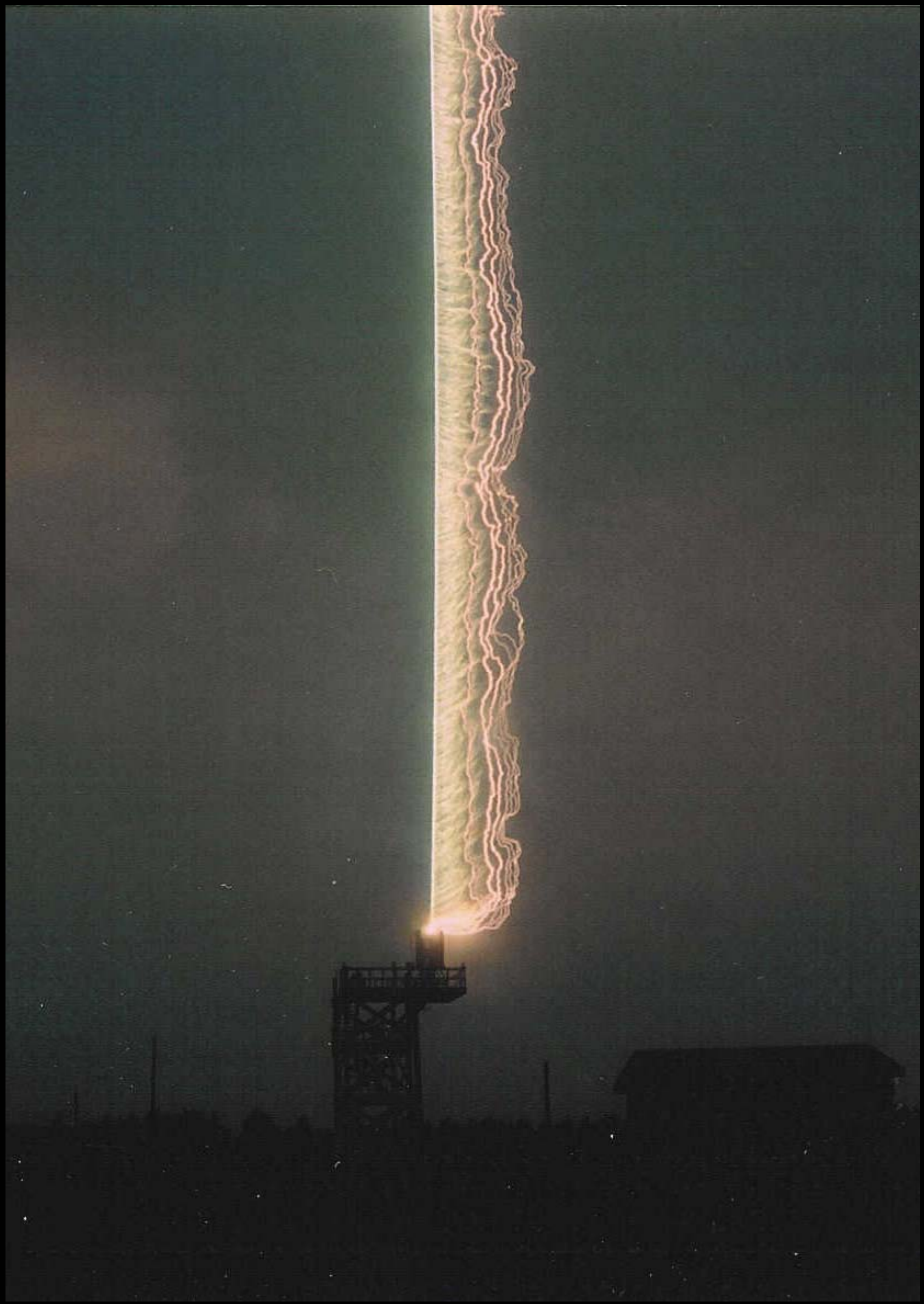


X-rays production is common in our atmosphere

- *In situ* balloon and aircraft observations have measured x-rays from thunderclouds (*e.g.* Eack *et al.* 1996; Eack *et al.* 2000; Parks *et al.* 1981; McCarthy and Parks 1995).

- Moore *et al.* 2001 found that energetic radiation is also produced by natural lightning during the stepped leader phase.

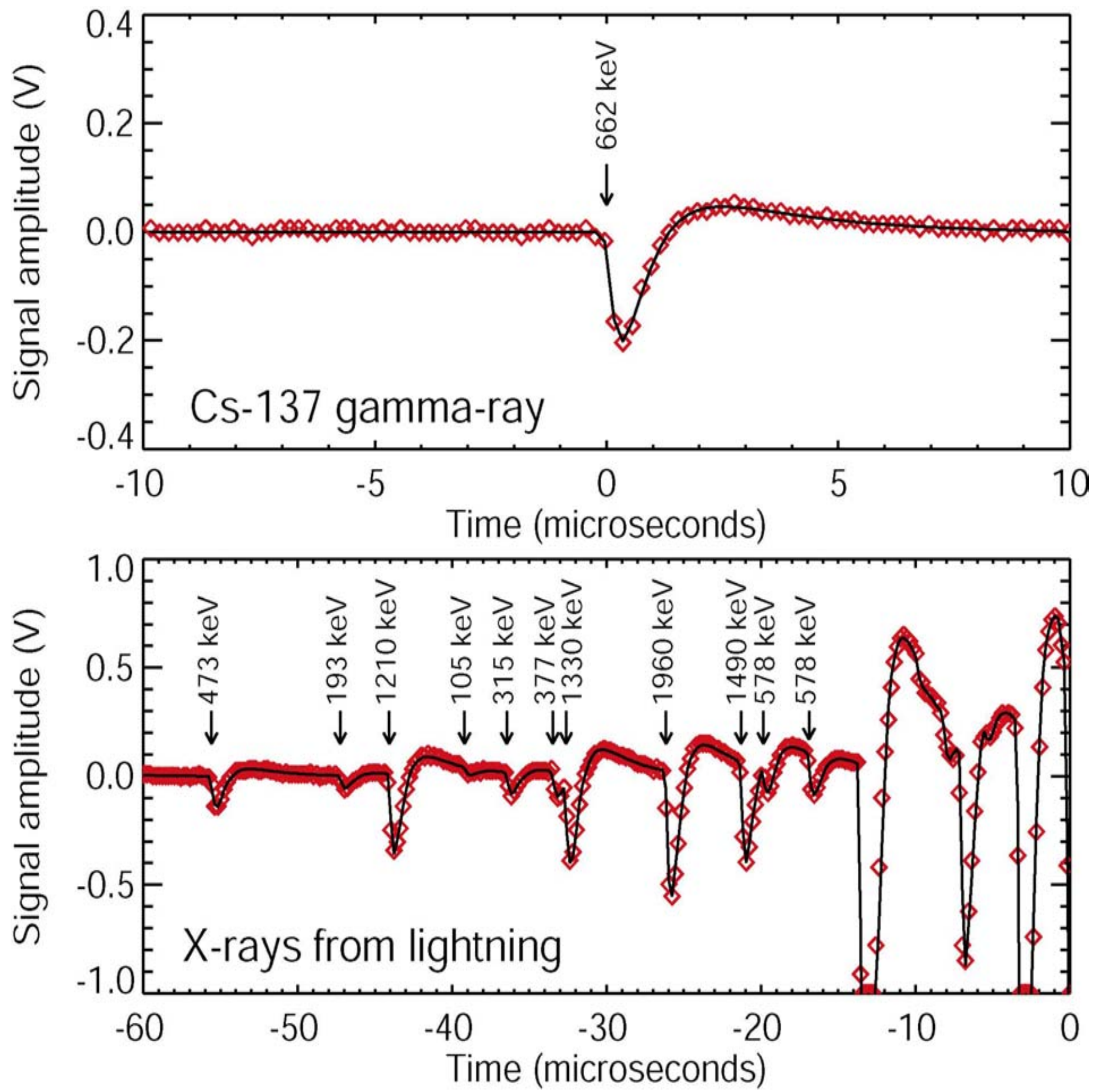
- Dwyer *et al.* 2003, 2004 found that x-rays are also produced by triggered lightning dart leaders.

- At present, the only viable explanation for these observations is the runaway breakdown of air.

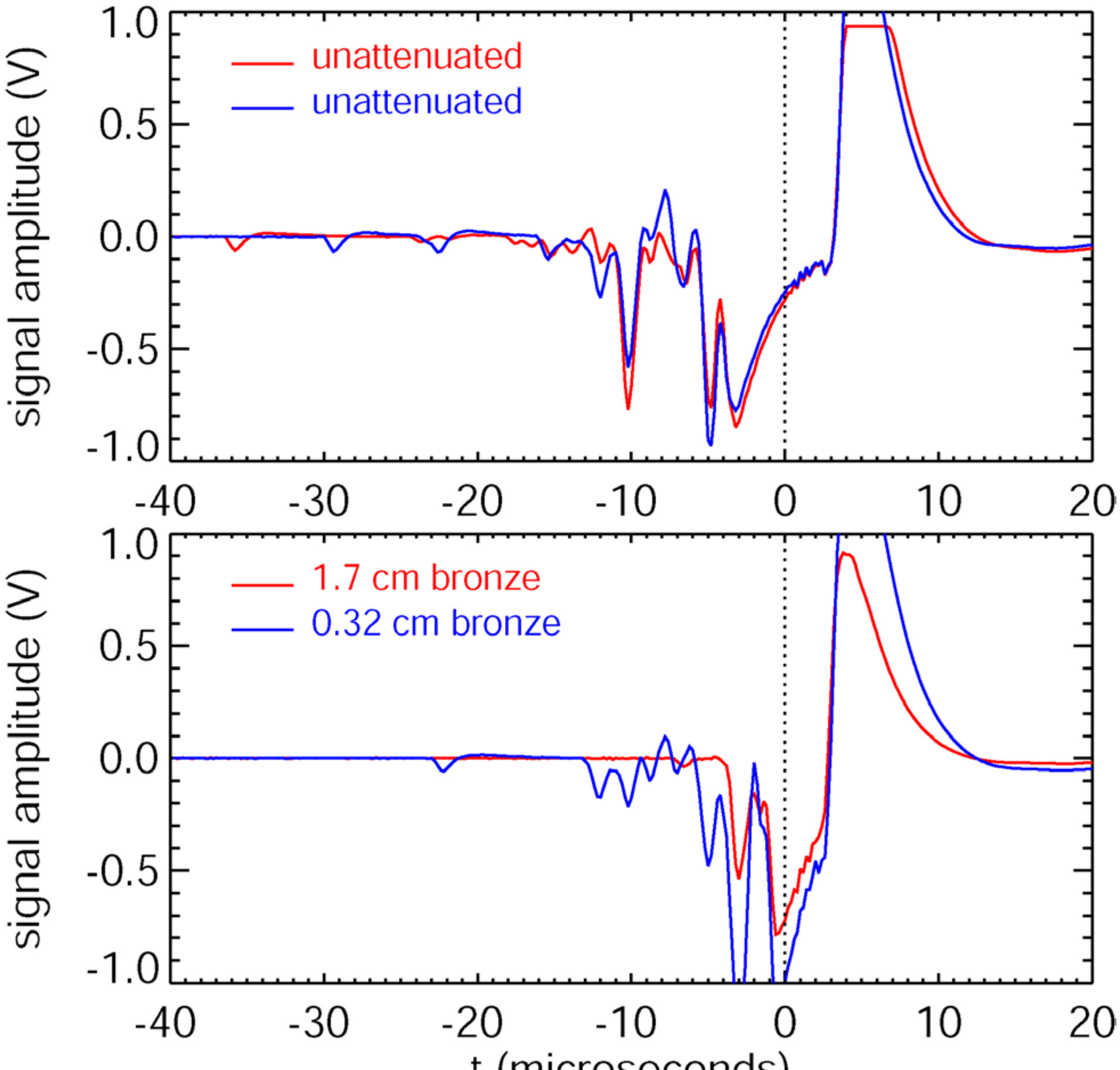
X-ray instruments in front of rocket launch tower used to trigger lightning

X-rays from triggered lightning

signals from NaI(Tl)/PMT detector anode

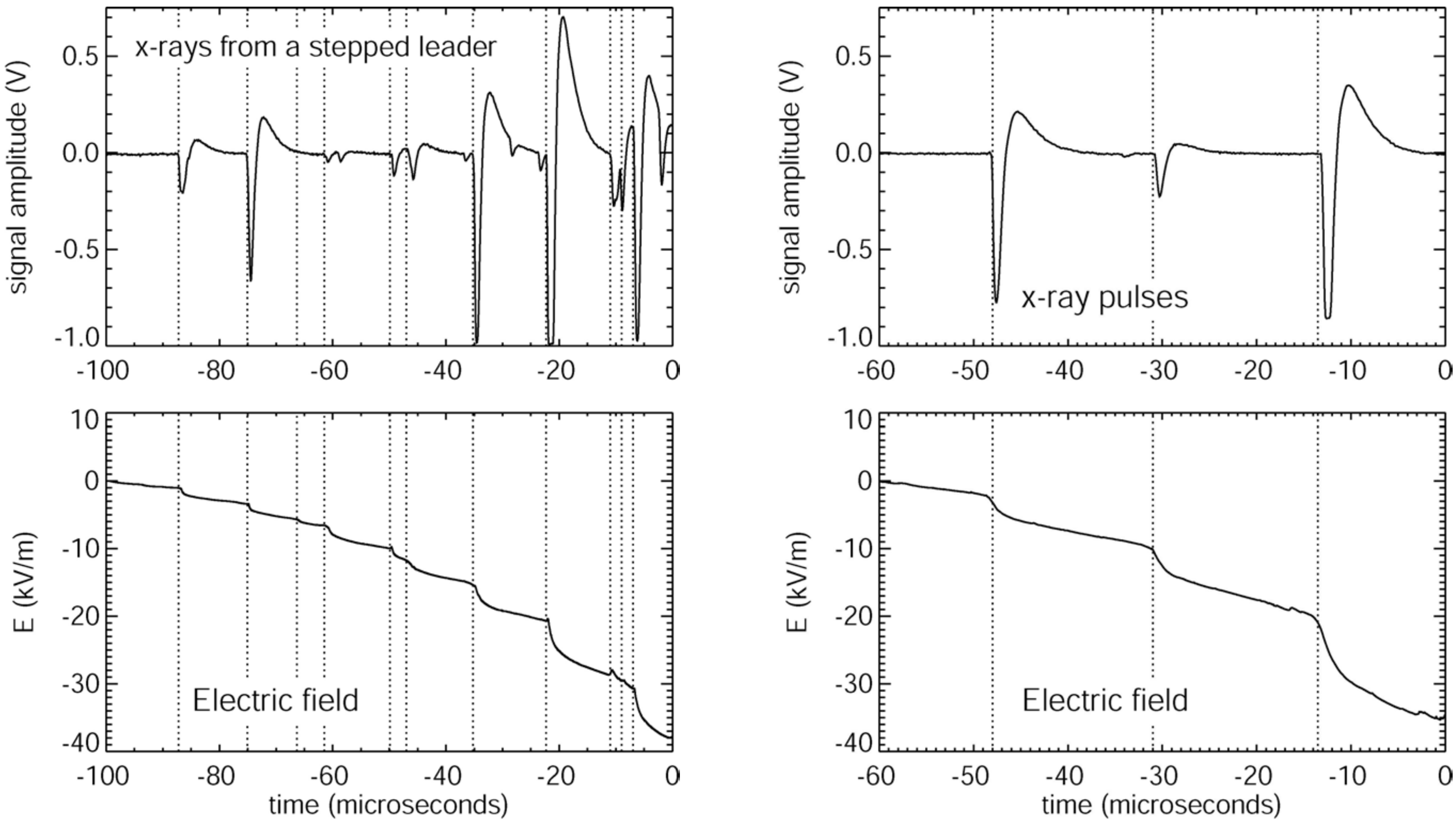


X-rays from triggered lightning



X-rays from natural cloud-to-ground lightning

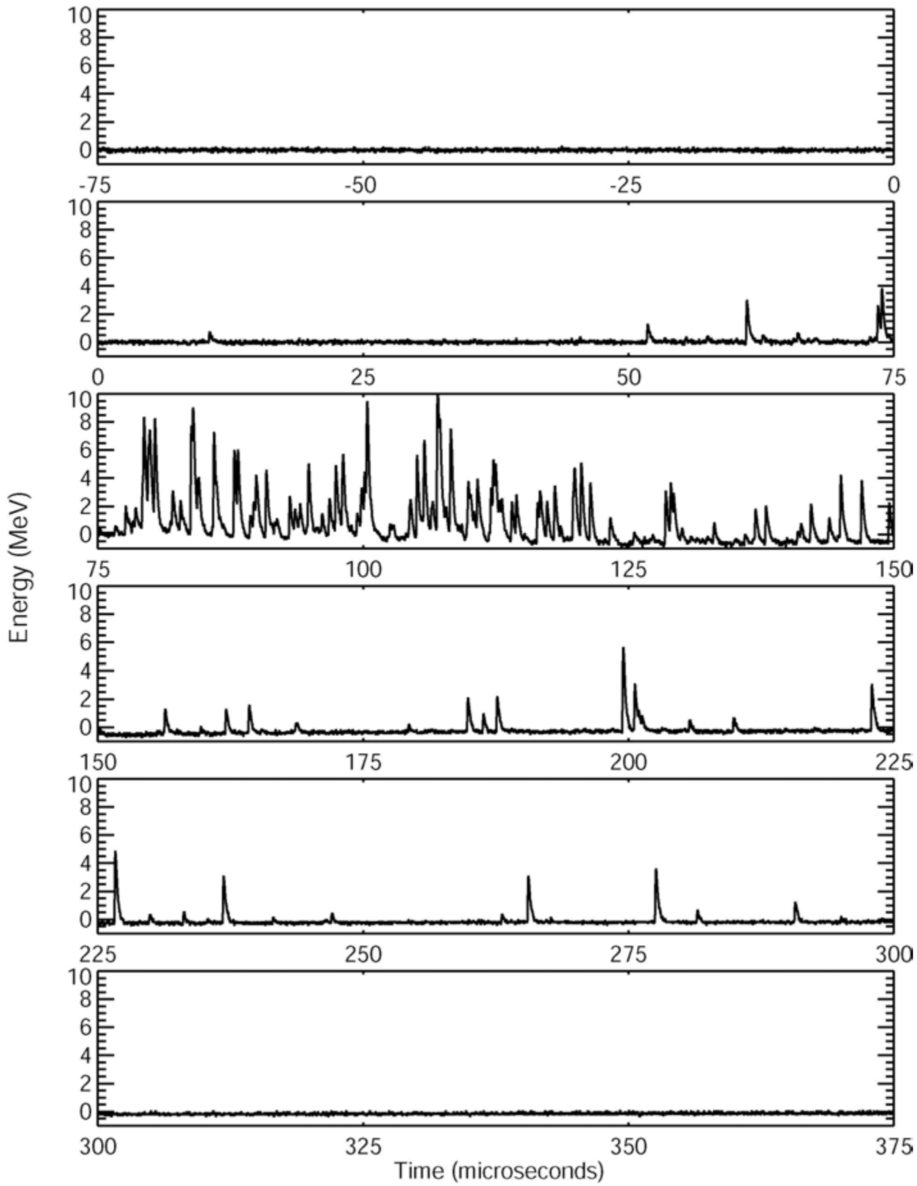
X-ray bursts are associated with the formation of the leader steps



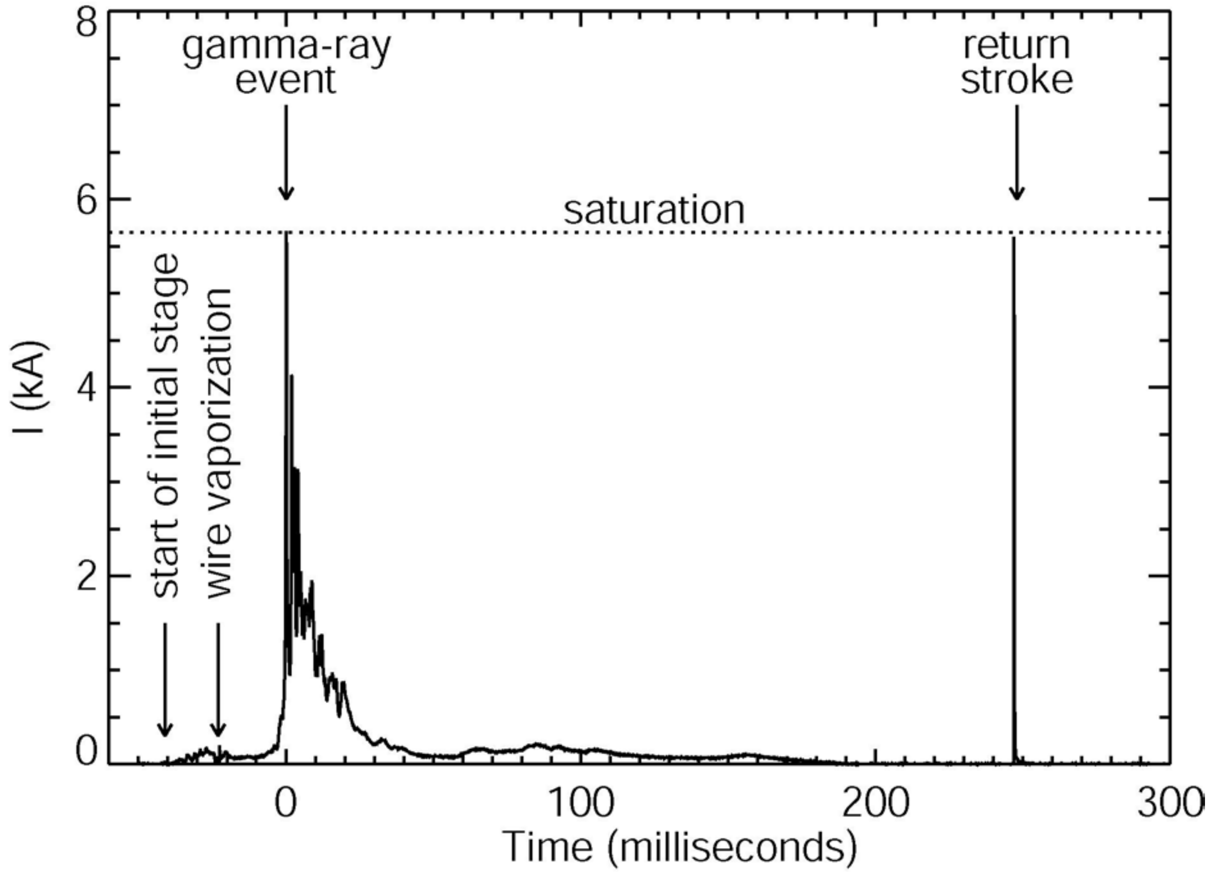
Properties of x-rays from natural lightning stepped leaders and triggered lightning dart leaders

- Detected energetic radiation is consistent with being entirely composed of x-rays.
- Bulk of x-rays have energies below 100 keV. Typically, the x-ray spectrum extends up to a few hundred keV. This suggests the x-rays are produced by energetic electrons with energies up to a few hundred keV.
- The x-rays arrive in a series of intense bursts, usually $<< 1$ μsec in duration.
- The x-rays usually begin about 1 msec before the return stroke for stepped leaders and a few tens of μsec before the return stroke for dart leaders.
- The x-ray emission almost always terminates within a couple of μsec after the start of the return stroke.
- X-rays are detected from about 80% of triggered lightning dart leaders and from all of the nearby natural lightning stepped leaders.
- Triggered lightning observations suggest that the beginning of the return stroke may also be a source of x-rays.
- X-ray bursts are associated with leader stepping

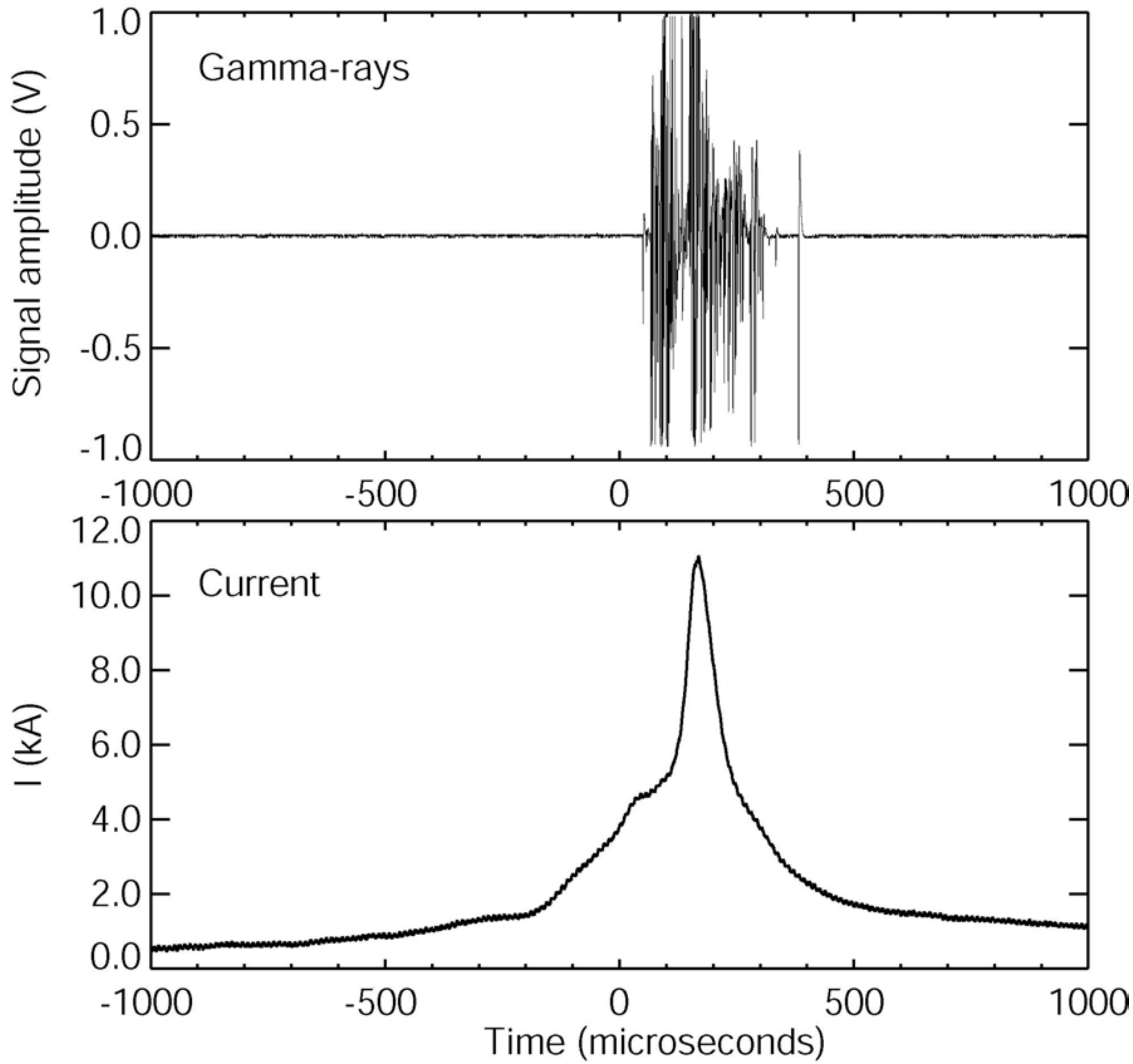
A ground level gamma-ray flash observed during the initial stage of rocket-triggered lightning



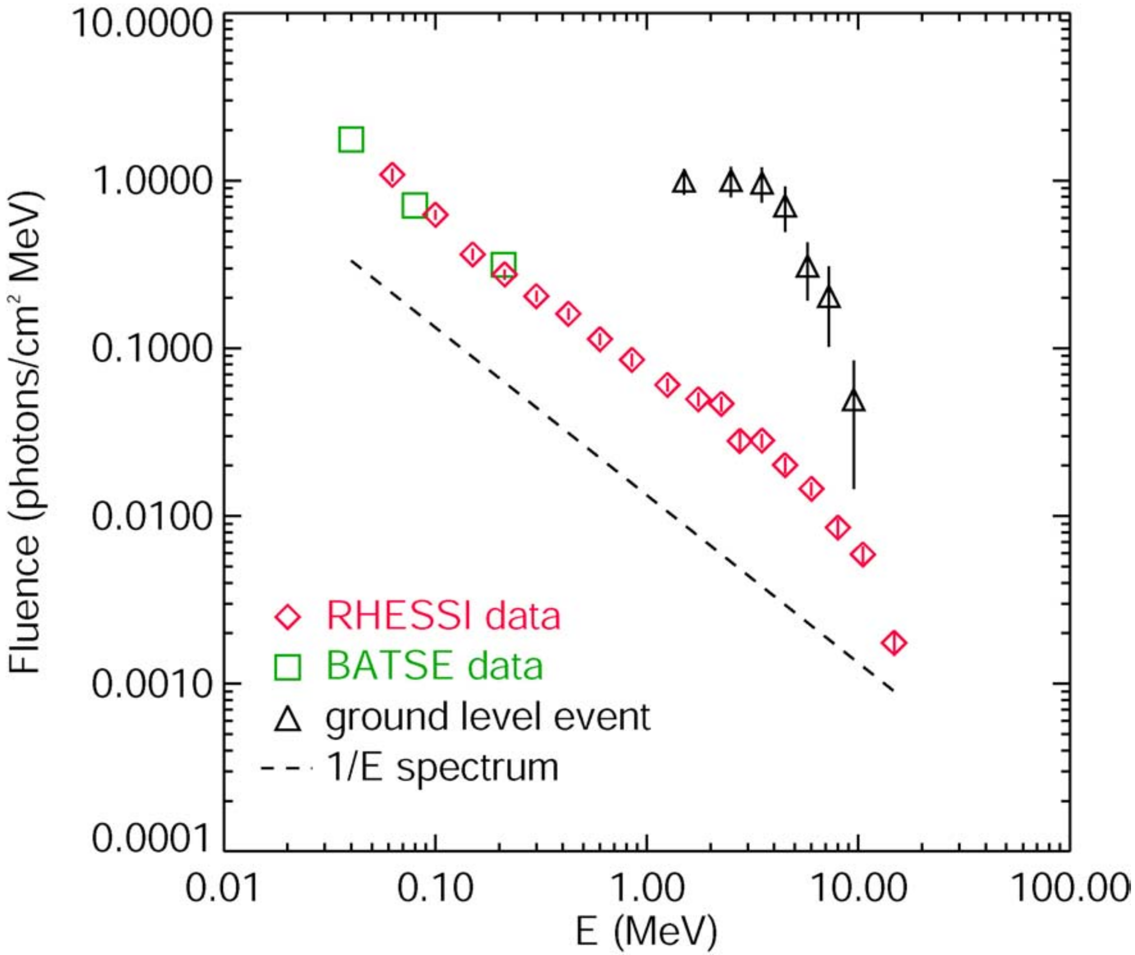
The gamma-ray flash occurred at the same time the upward leader should have reached the cloud charge several km above the ground



Close up of gamma-ray flash as seen by a second detector



Energy spectrum of ground level event and TGFs



Monte Carlo simulation of the runaway breakdown of air

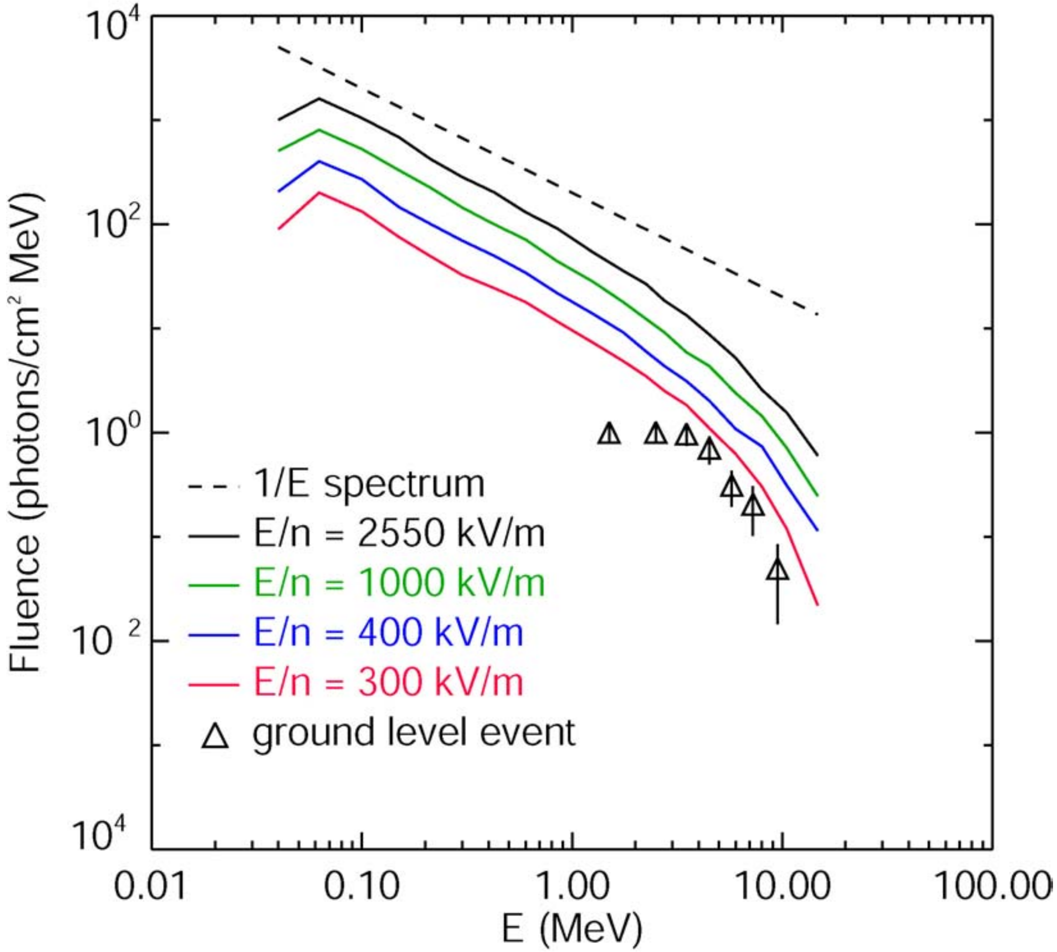
- Three-dimensional Monte Carlo simulation of the runaway breakdown of air has been developed at Florida Tech. It includes in an accurate form, all the important interactions involving runaway electrons:
  - Energy losses through ionization and atomic excitation.
  - Møller scattering for secondary electron production.
  - Elastic scattering is fully simulated using a shielded-Coulomb potential, rather than relying on a diffusion approximation.
  - Bremsstrahlung production of x-rays and gamma-rays and the subsequent propagation of the photons, including photoelectric absorption in nitrogen, oxygen and argon, Compton scattering and pair production.
  - Positron propagation and the generation of energetic seed electrons via Bhabha scattering of positrons and via Compton scattering and photoelectric absorption of energetic photons.
  - Bremsstrahlung production from all secondary electrons and positrons and positron annihilation gamma-rays.

- The simulation was used to model the ground level and TGF spectra for various electric field strengths, source altitudes and source geometries.

Bremsstrahlung spectra produced by runaway breakdown for different electric field strengths

Runaway breakdown threshold $E_{th}/n = 284$ kV/m

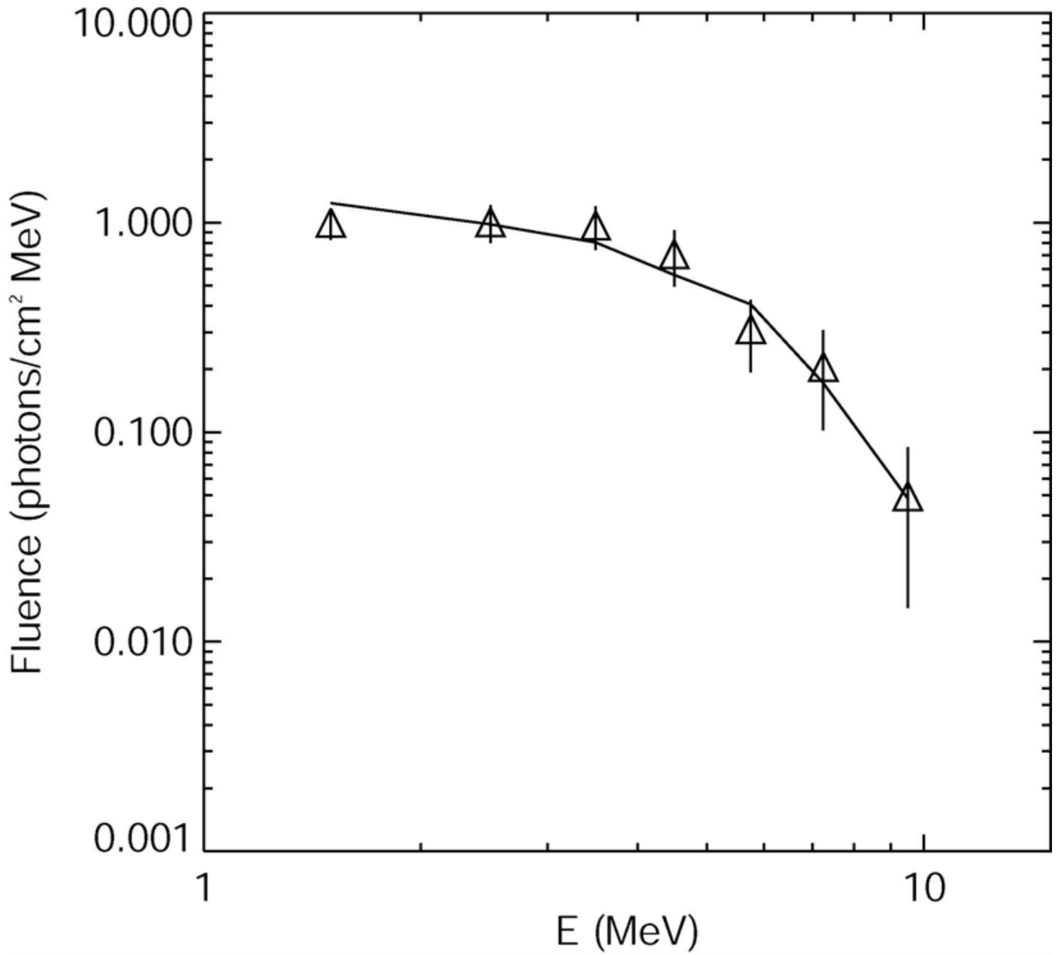
Spectra calculated at 13 g/cm^2 (100 m at STP)



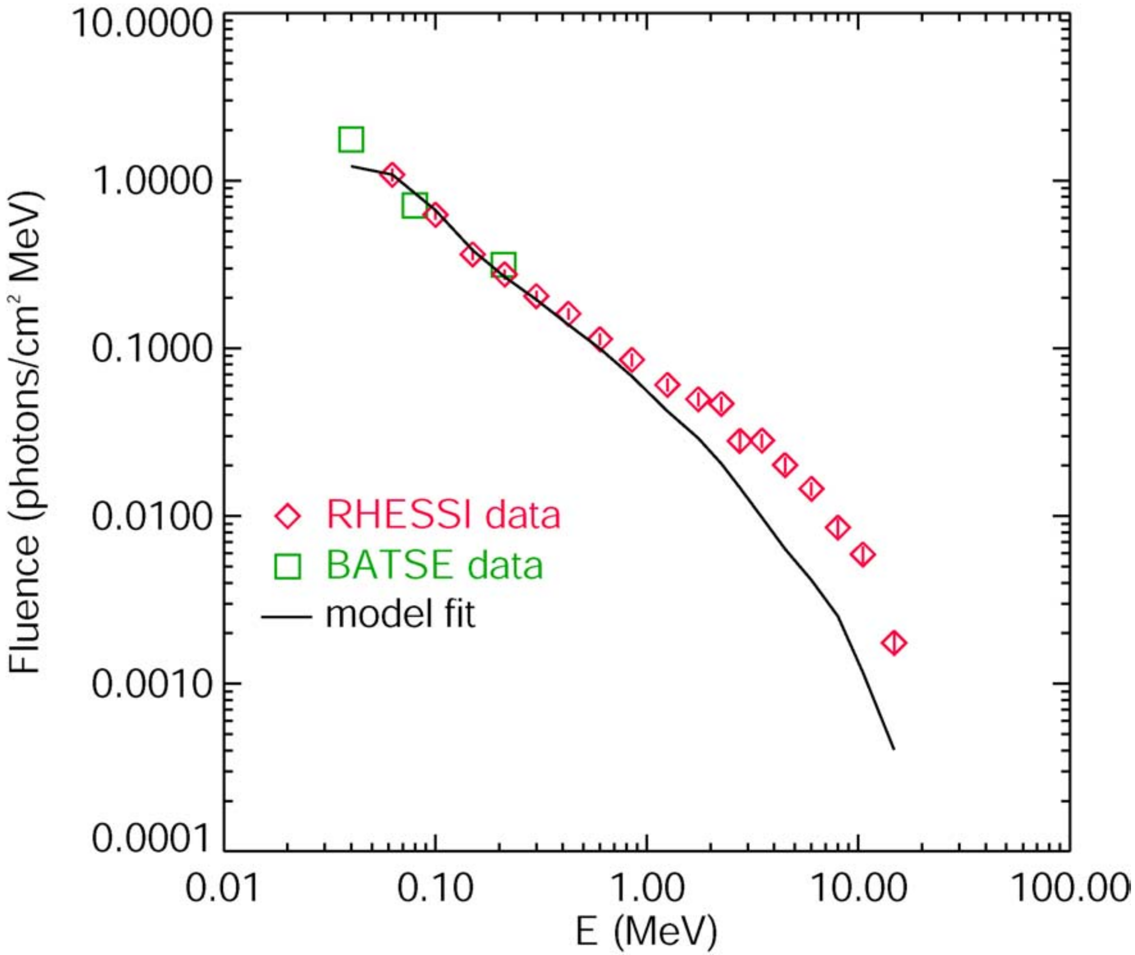
Energy spectrum of ground level flash along with model fit for runaway breakdown at 4 km

E/n = 400 kV/m

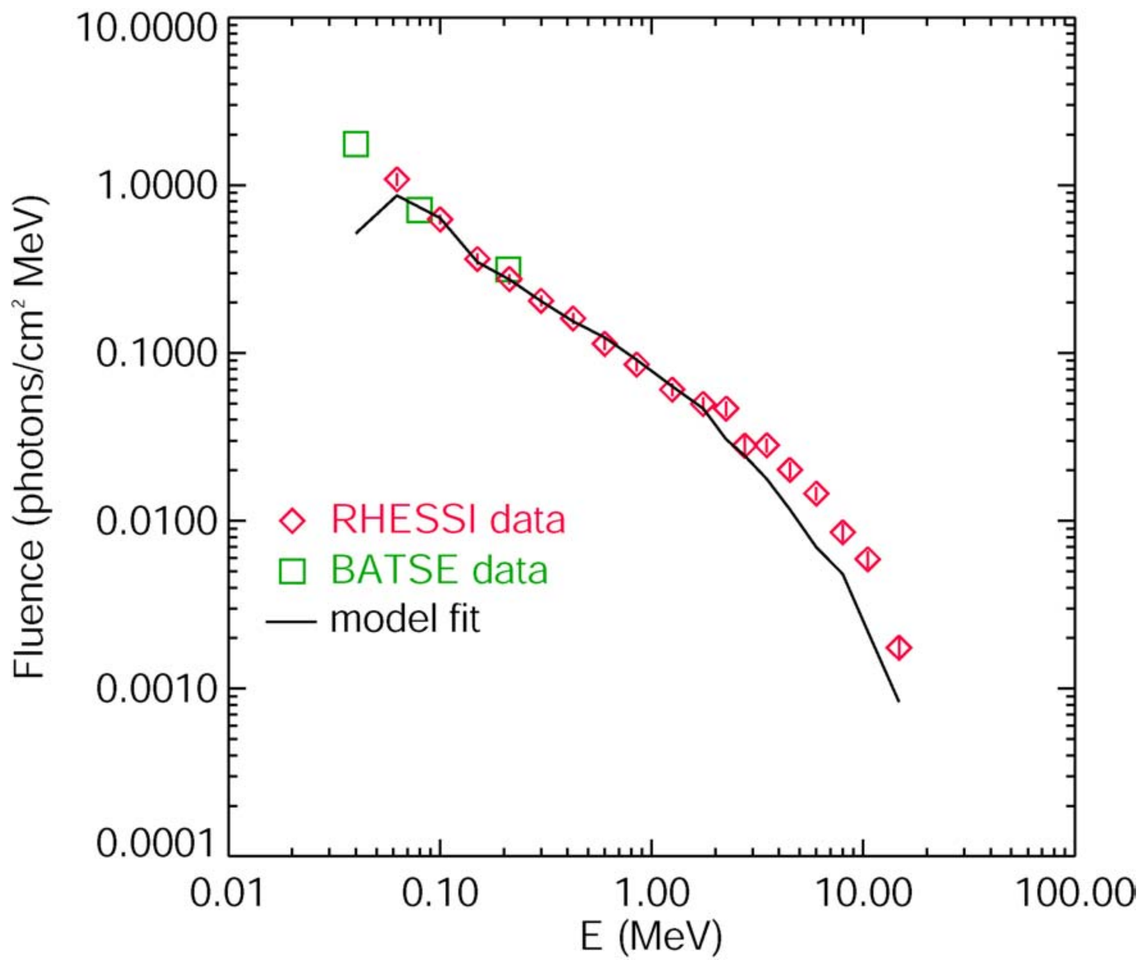
The source is beamed downward and the detector is ~1 km off axis



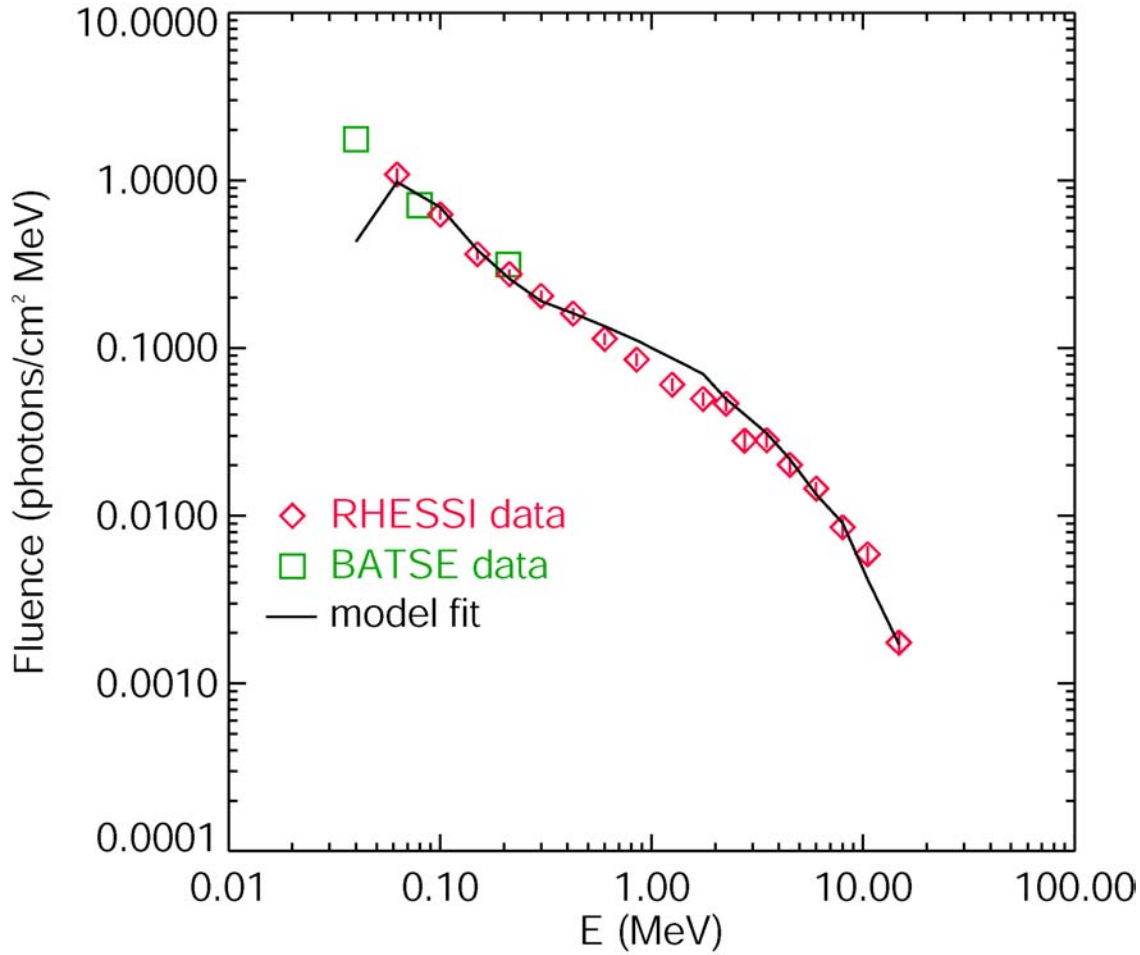
TGF spectrum and model fit of runaway breakdown at top of atmosphere (0 g/cm^2) with beamed emission



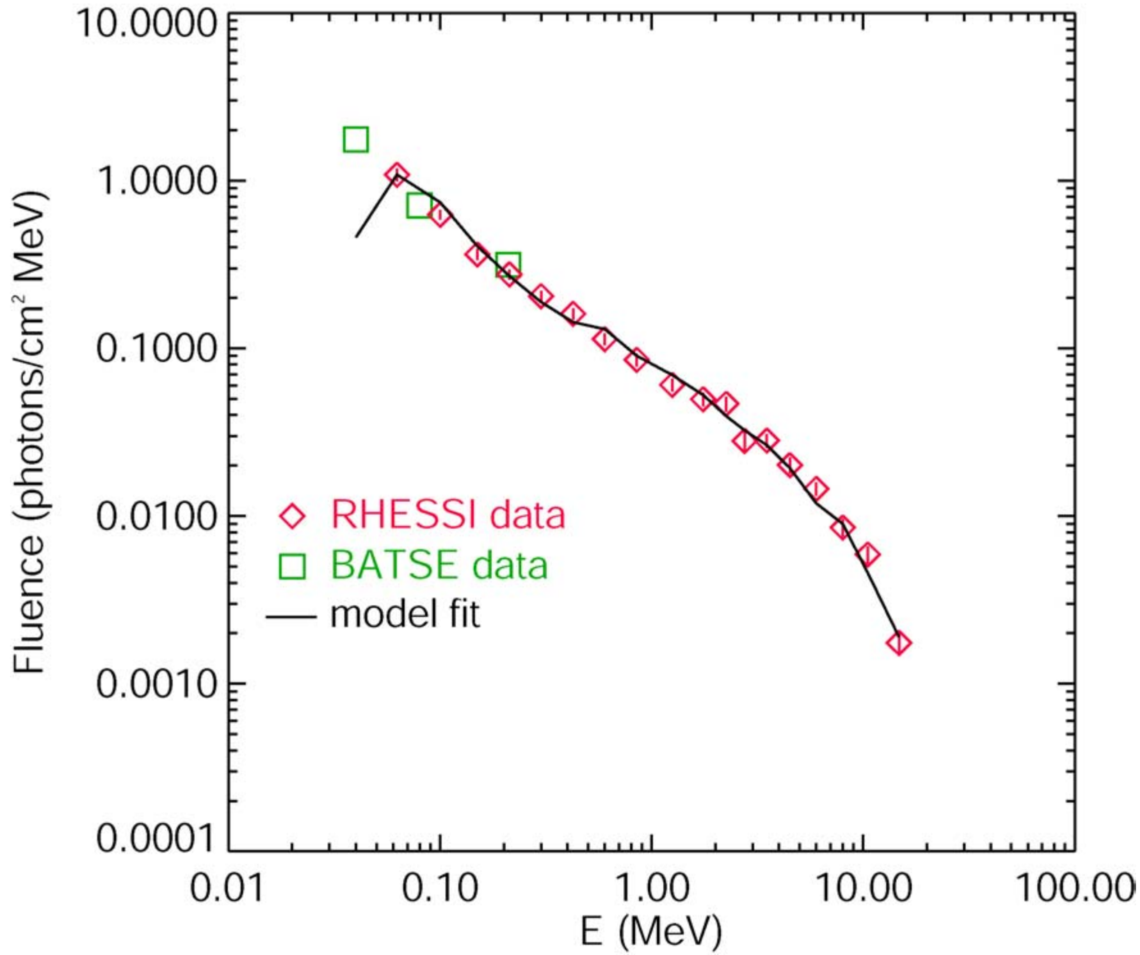
TGF spectrum and model fit of runaway breakdown at 30 km ($13\ g/cm^2$) with beamed emission



TGF spectrum and model fit of runaway breakdown at 23 km ($30\ g/cm^2$) with beamed emission



TGF spectrum and model fit for runaway breakdown at 16.5 km ($100\ g/cm^2$) with isotropic emission



Summary

- Ground level gamma-ray flash can be modeled with runaway breakdown at 4 km altitude if the source is beamed downward and the detector is ~1 km off axis.
- The RHESSI TGF spectrum can be reasonably well modeled with runaway breakdown between 20 - 30 km if the source is beamed.
- The RHESSI TGF spectrum was best fit with runaway breakdown at 16.5 km with an isotropic source.
- Since for low geographic latitudes the tropopause is often at 16.5 km, the RHESSI TGFs could possibly originate from inside thunderclouds.
- The lowest energy BATSE TGF data point as calculated by Nemiroff *et al*. (1997) does not appear to be consistent with the RHESSI spectrum.