RREA emission as thunderstorm discharge competing with lightning

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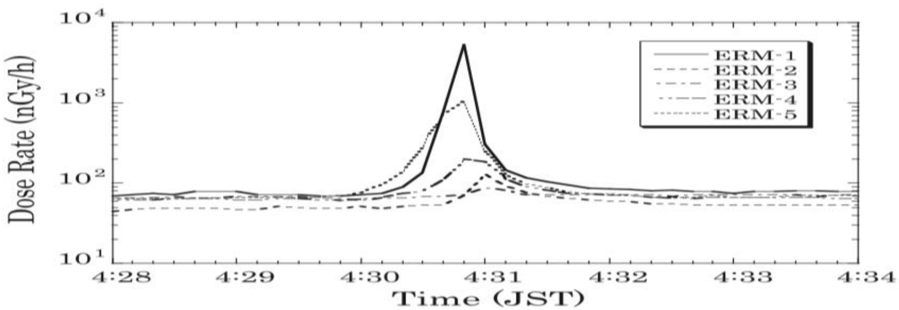
Talk Overview

- Introduction to gamma-ray glows
- Quick overview of mechanisms to explain emission
- ADELE instrument
- ADELE glow results from 2009 campaign
- Glow/lightning relationship
- Modeling of August 21 Glow
- New Instrument Plans

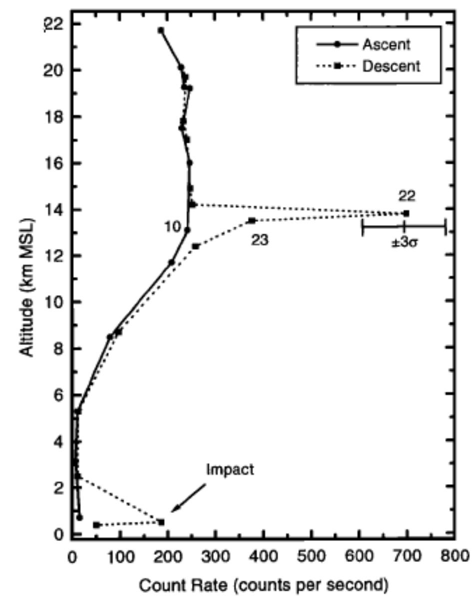
Gamma-ray Glows

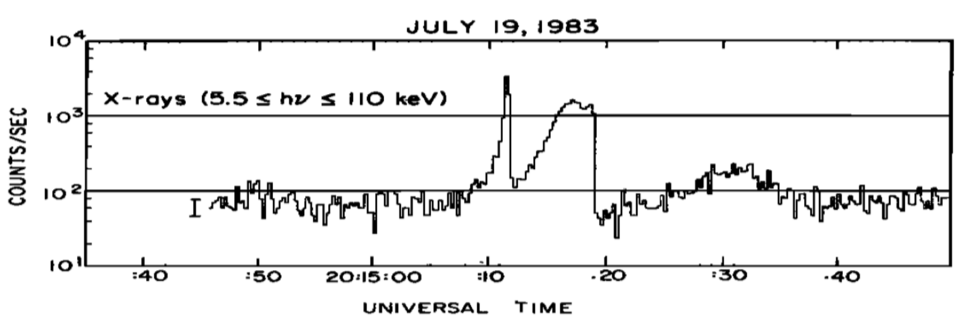
Long duration (seconds - tens of minutes) gamma-ray emission from thunderclouds



Ground measurements by Torii et al. 2002

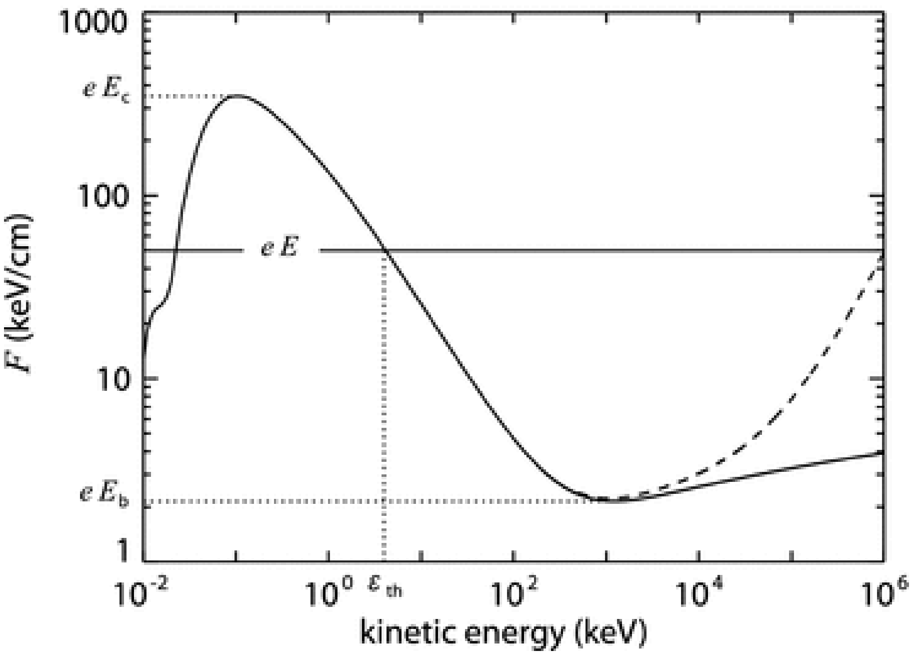
Balloon experiments by Eack et al. 2002





Airplane measurements by McCarthy & Parks 1985

Relativistic Runaway

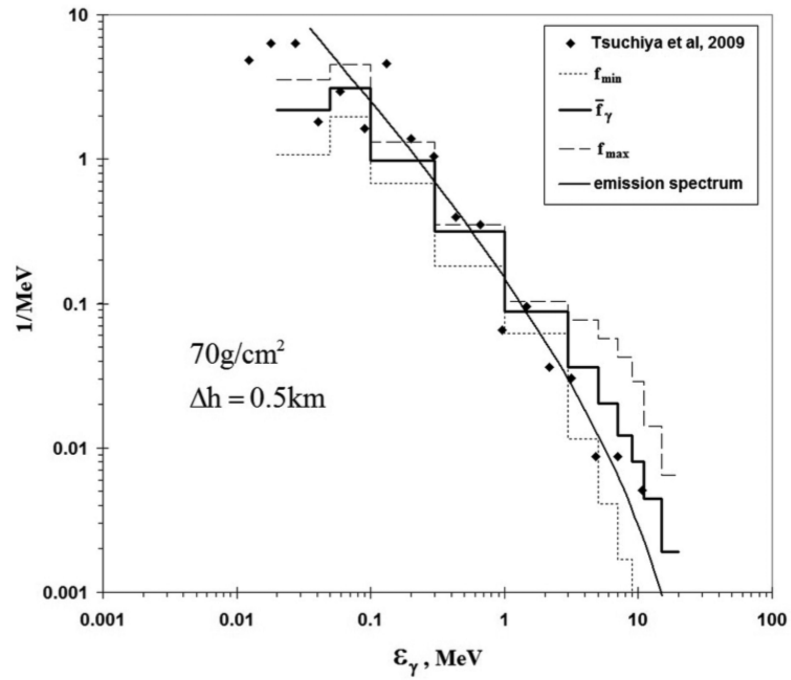


From Dwyer et al. 2012

- In 1925, C.T.R. Wilson predicted runaway
- Electrons will gain energy faster than inelastic scattering causes energy losses and it will "run away"
- Hypothesized this would occur above thunderclouds
- Fields above E_c result in "cold runaway"—stepped leaders

RREA Mechanism

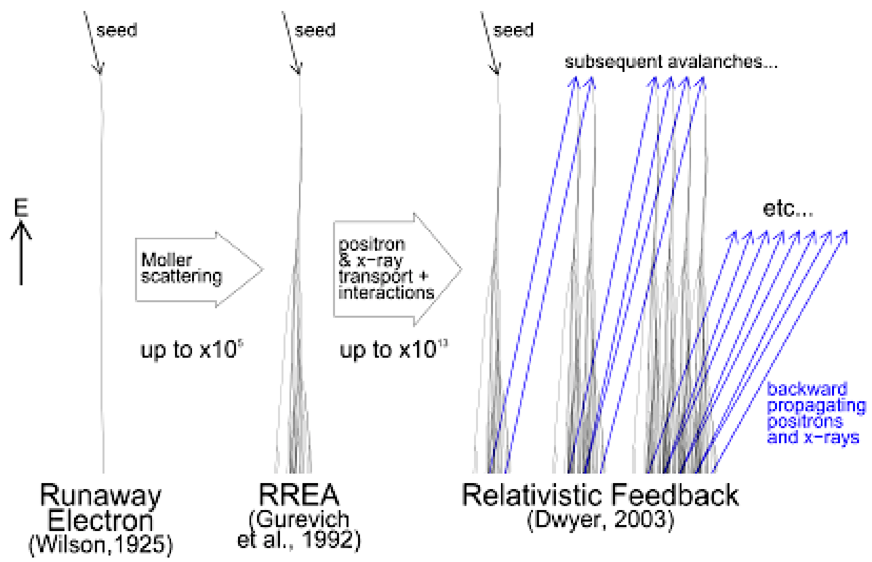
- When Møller scattering is included the number of seed electrons increases (Gurevich et al. 1992)
- Relativistic Runaway Electron Avalanche
- Seed electrons from cosmic rays, radioactive decays or cold runaway in leader tips
- Agrees well with glow and TGF spectra



From Babich et al. 2010 – Glow spectra compared to RREA model propagated through air

RREA with Feedback

- ϒ's pair produce or Compton backscatter causing new avalanches via Bhabha/Compton scattering or photoelectric absorption (Dwyer 2003)
- Allows for extremely high fluence of TGFs

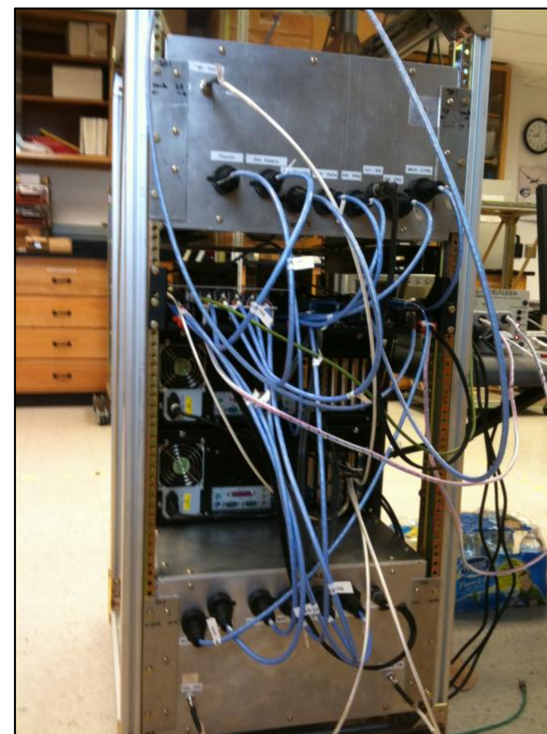


Dwyer et al. 2012

ADELE Instrument – Version 1.0

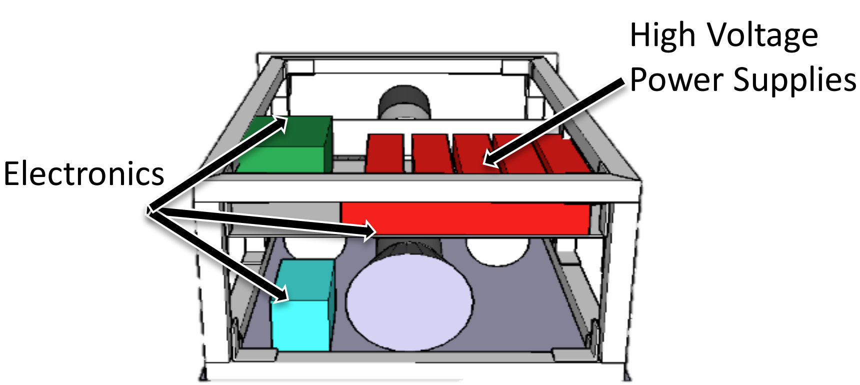
- Array of six gamma-ray detectors with dual-mode data acquisition – continual and triggered

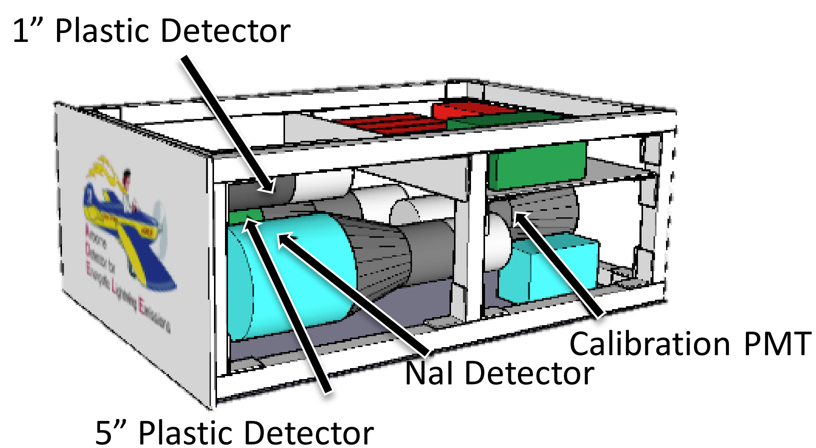
UCSC FIT NSF
ADELE
Airborne
Detector for
Energetic Lightning Emissions



Inside the sensor heads

- 5”X5” NaI Detector for energy resolution. Runs in triggered mode.
- 5”X5” Plastic Scintillator – four energy channels for rough spectra, trigger NaI, continual mode
- 1”X1” Plastic Scintillator – 4 energy channels. Less likely to saturate (3 million counts/sec), continual mode
- PMTs (empty included for noise detection), fast-chain electronics
- Lead shielding for directionality



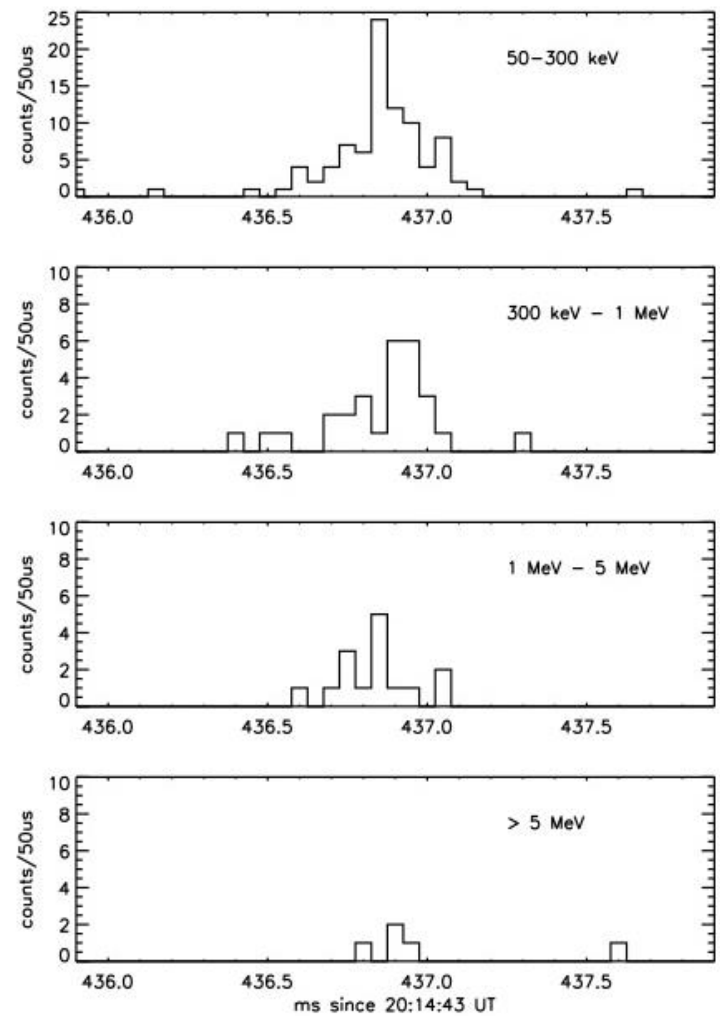


Summer 2009 Campaign

- Flew on the NCAR Gulfstream V
- 37 flight hours in areas near Colorado/Florida from August 7-September 2
- 1 TGF observed, 12 gamma-ray glows observed

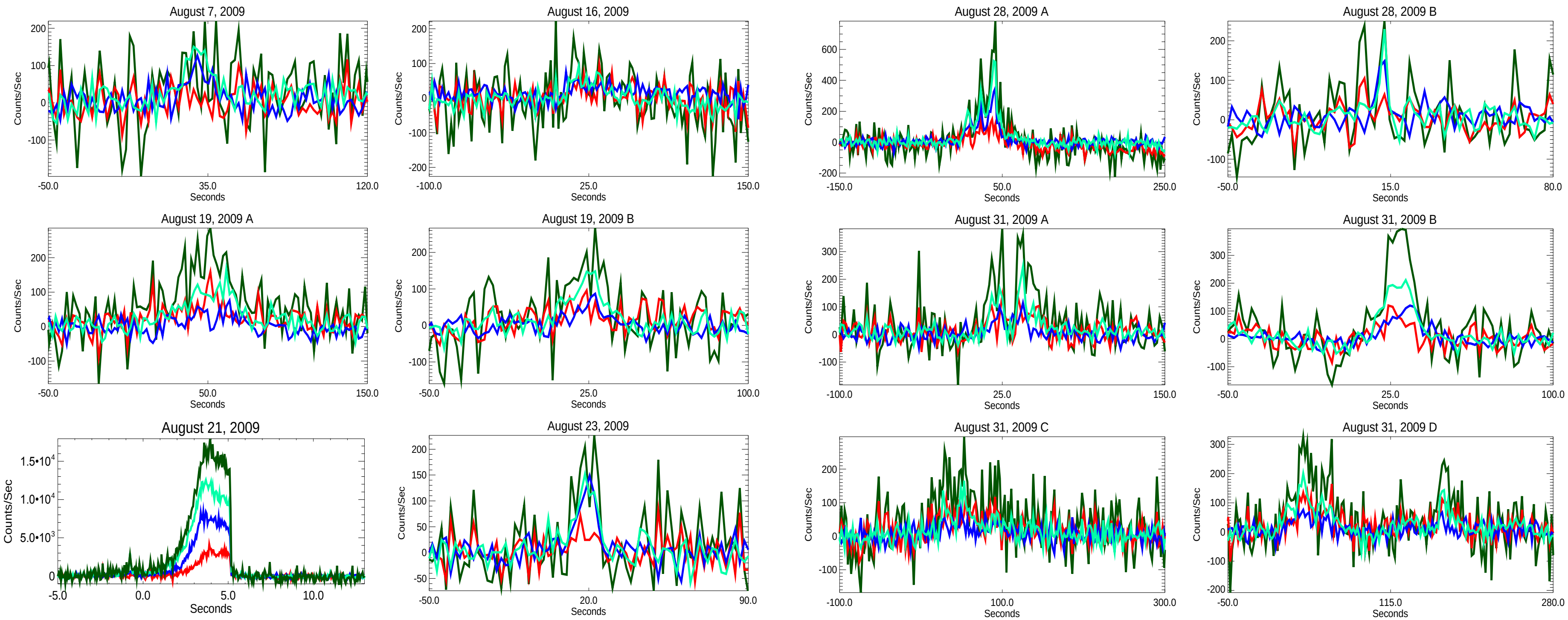
First TGF seen by an airplane

- TGF Observed on August 21, 2009 at 20:14:43.437 UT from the above the coast in Georgia
- 41 counts >300 keV
- ~10 km away from instrument



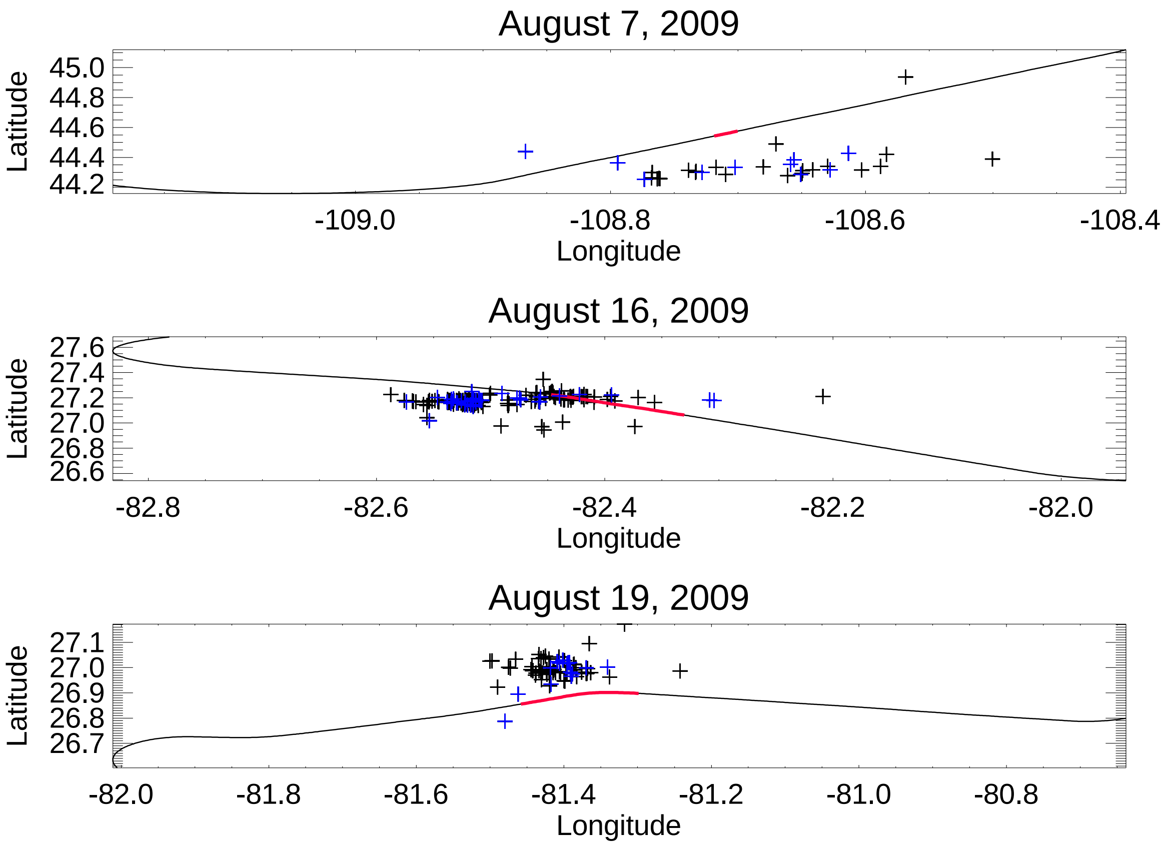
The ADELE Glows

- 12 glows detected over 7 different flights



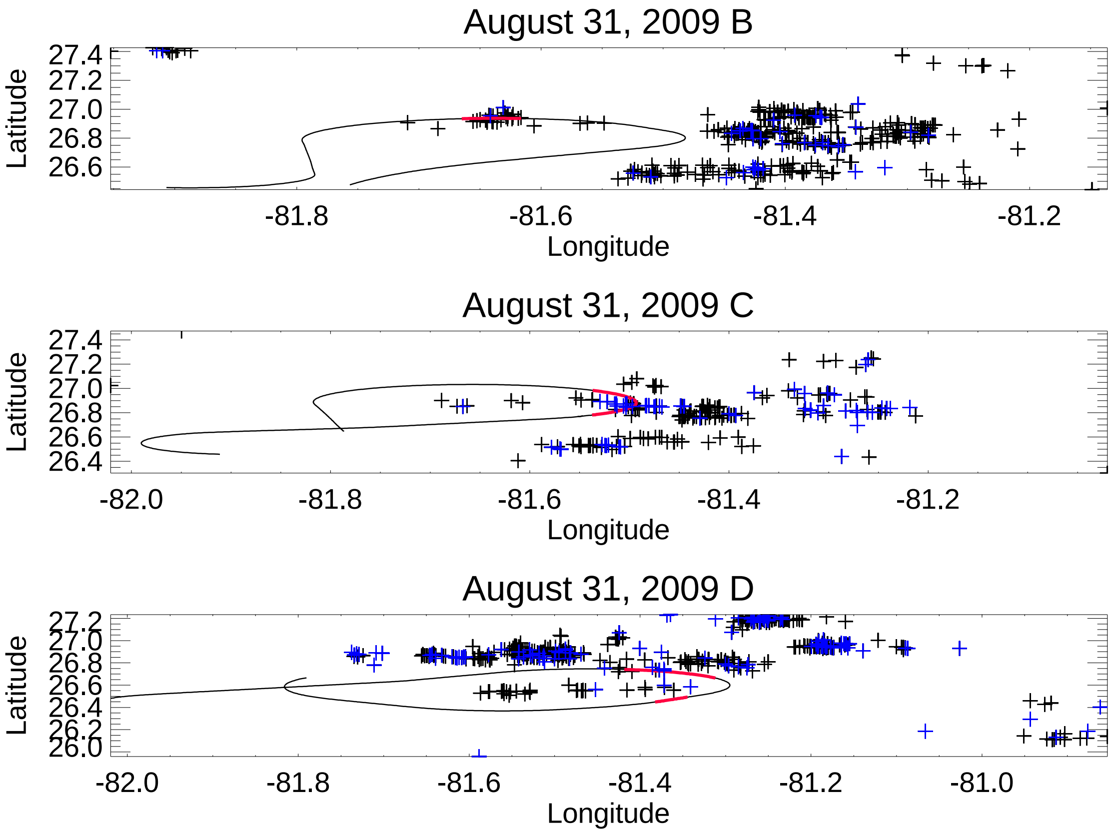
Dark green line is 50-300 keV counts/sec divided by 3. Turquoise line is 300-1000 keV counts/sec. Blue line is 1-5 MeV counts/sec. Red line is >5 MeV counts/sec.

Glows and their relationship to lightning



Black crosses are lightning +/- 5 minutes and 50 km of the glow. Blue cross marks are lightning within +/- 30 seconds of the glow. The path is the plane trajectory and the red portion is during the glow.

Glows and their relationship to lightning



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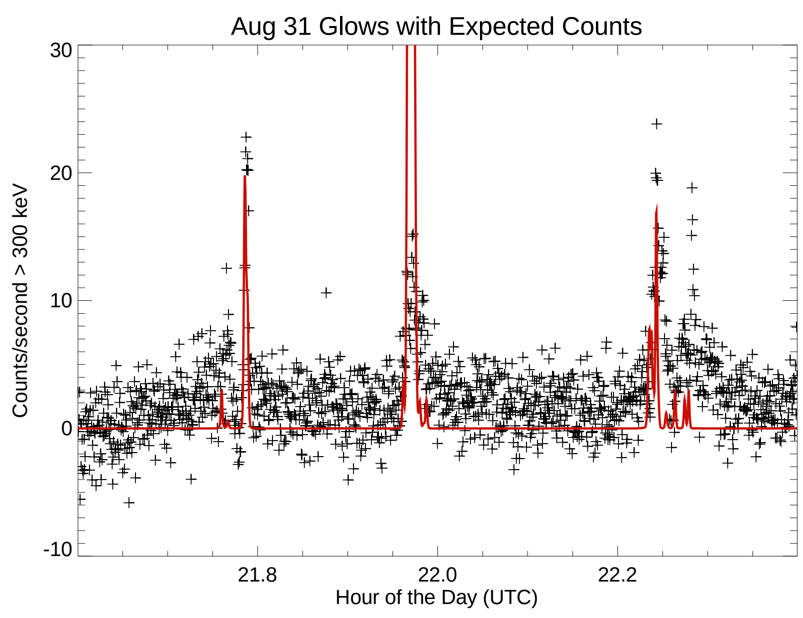
Lightning Model

Using the first two stages of our Monte Carlo simulation of RREA with feedback (no instrument response), found the dependence on glow intensity from distance to an active cell

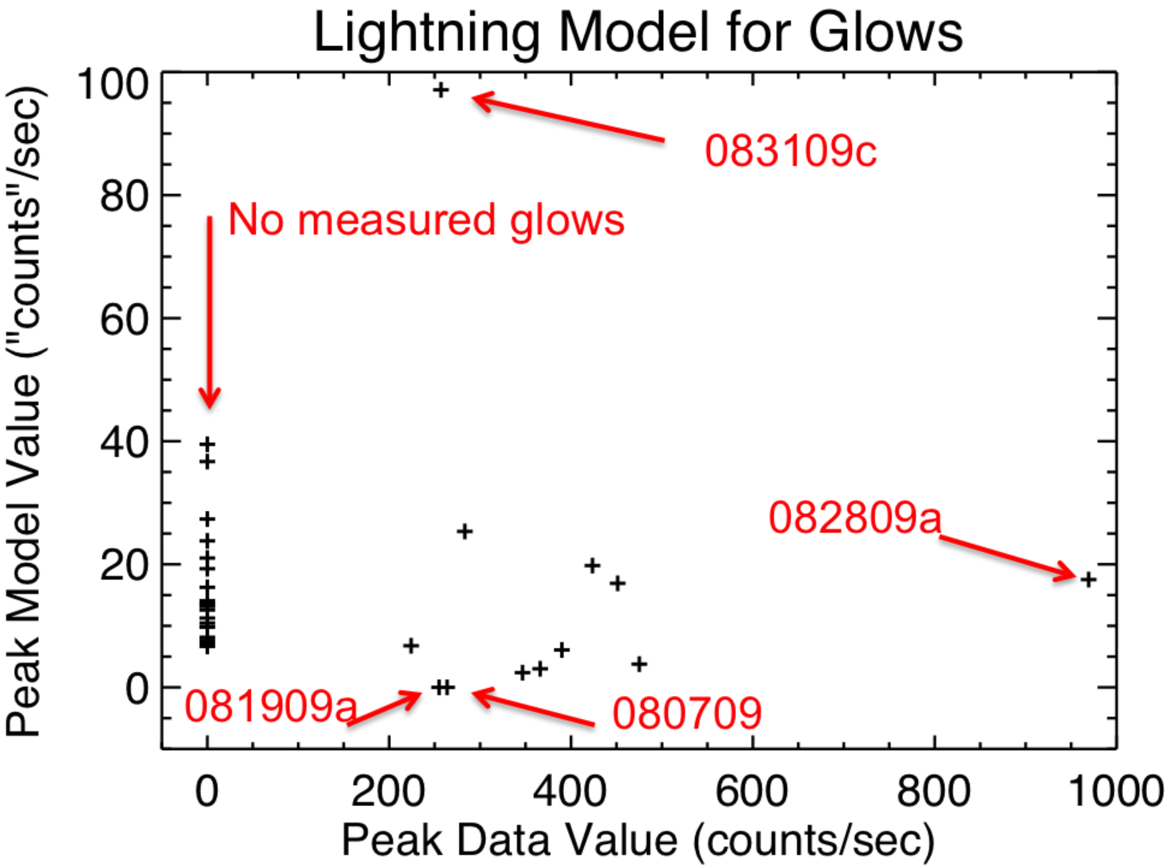
$$E(t) = e^{\frac{-d_{f(t)}}{d_0}} + Ae^{\frac{-d_f}{2\sigma^2}}$$

We convolved this equation with NLDN, WTLN and USPLN lightning distances to the instrument as a function of time

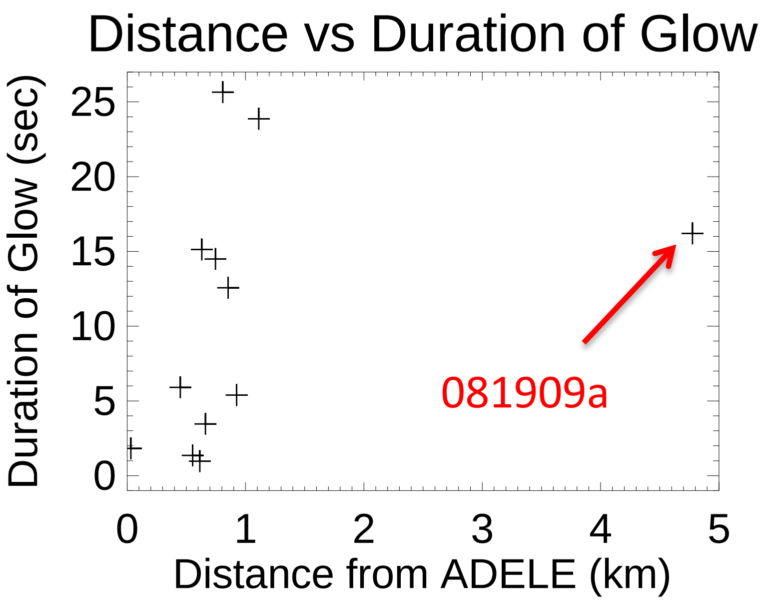


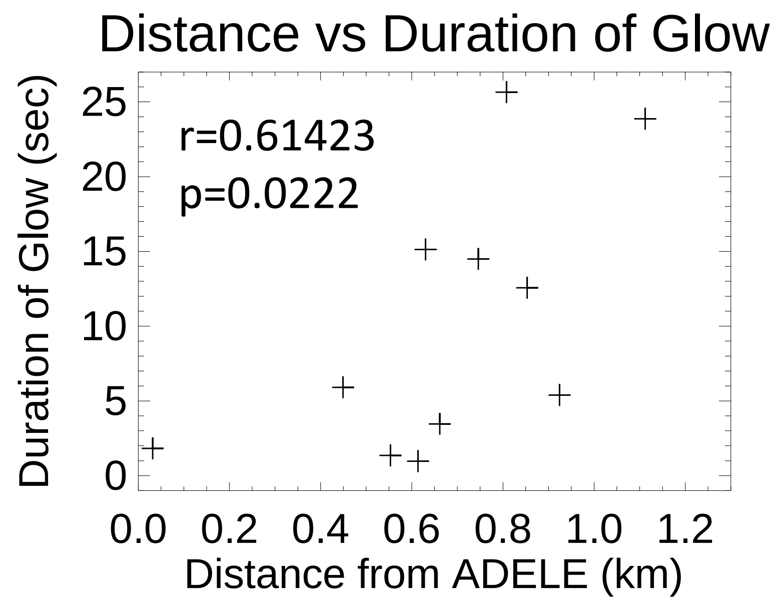
Success of Model

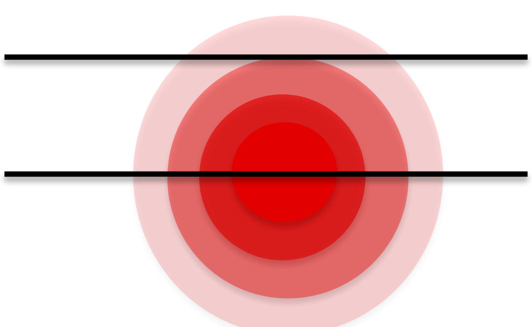
- 11/149 times there was a peak in the model, there was a glow
- All glows except for the glow in CO had a peak in the model



Distance versus Glow Width



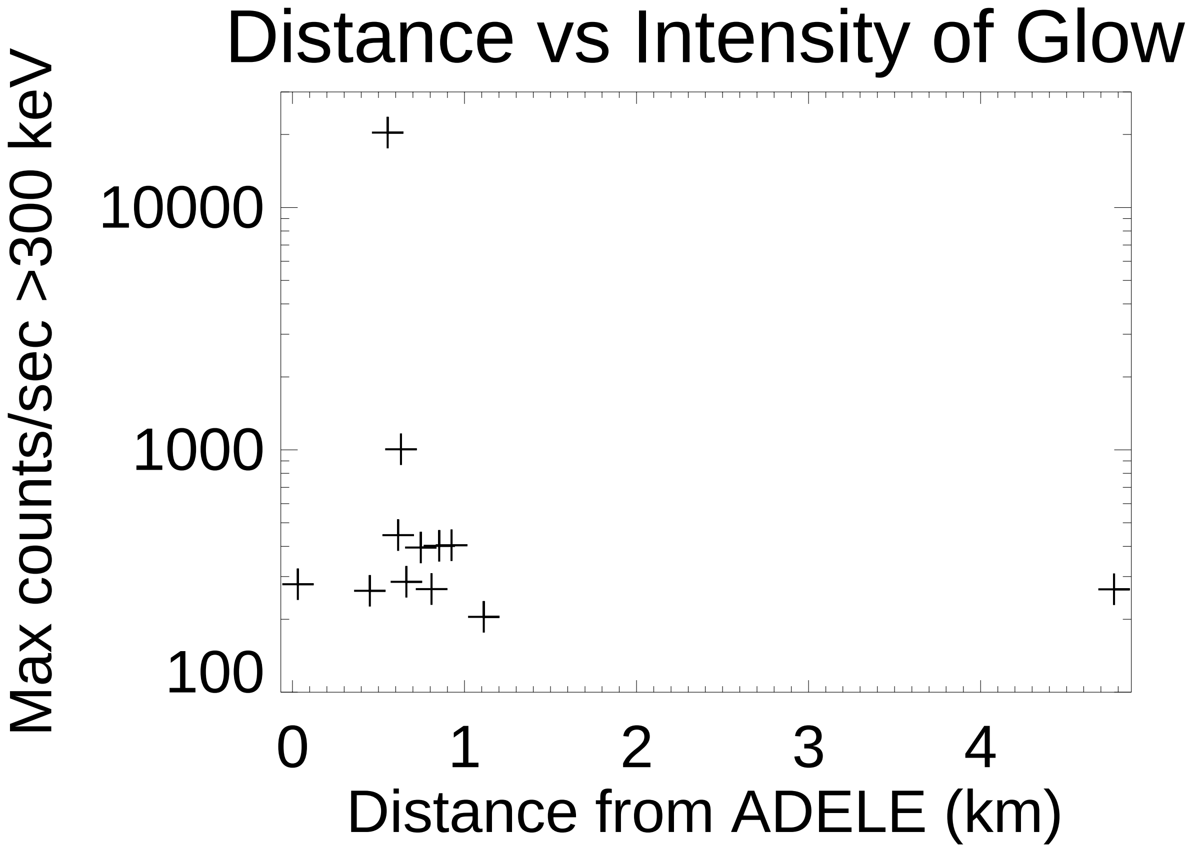




Outlier on August 19 removed-
Linear relationship is found

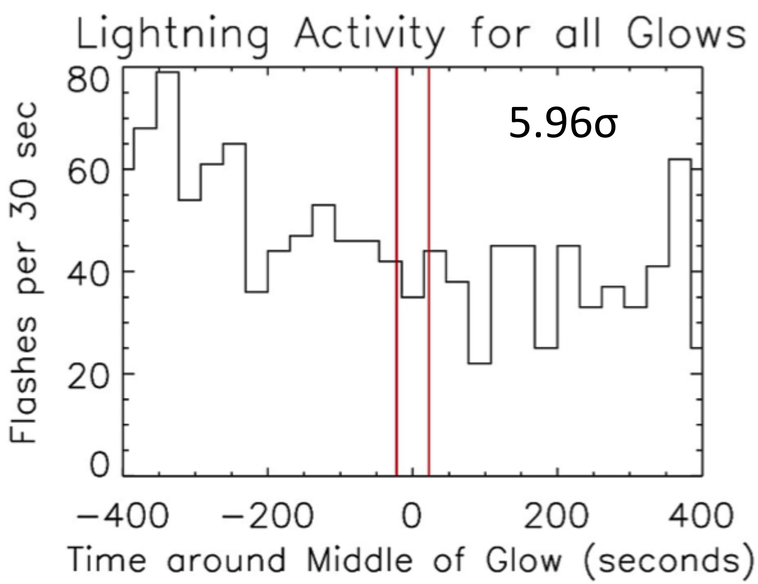
Distance versus Brightness

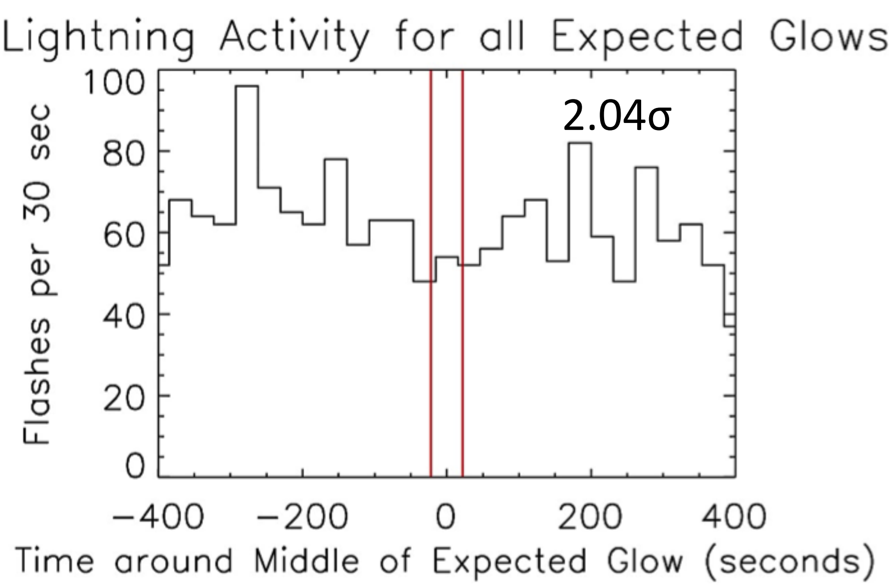
- No linear relationship between distance and brightness- even when outliers are removed
- Can faint glows still be the same brightness as bright glows?



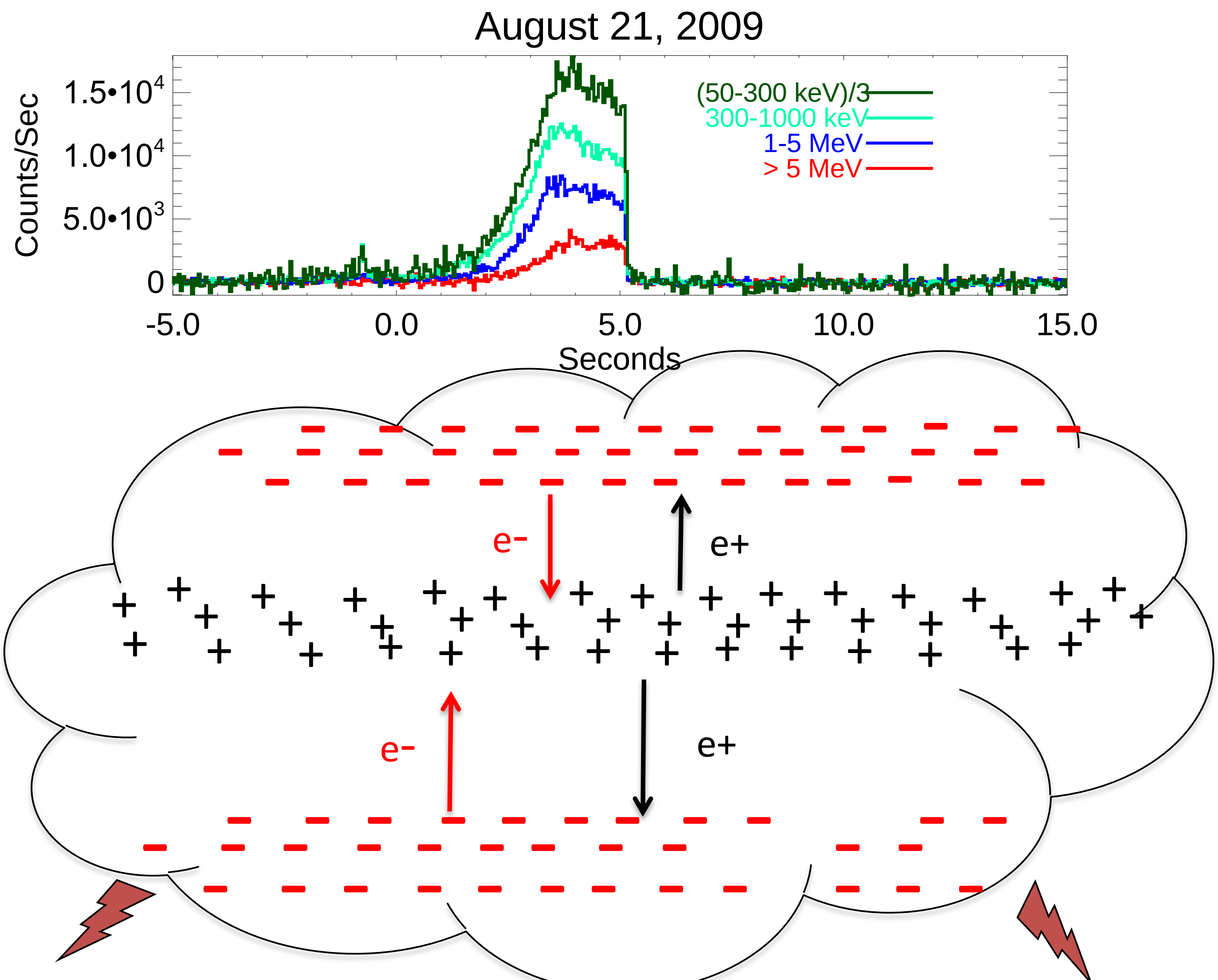
Lightning Activity near Glows

- Lightning activity suppressed after glow
- Could be glows can only happen once lightning activity dies down
- Glows discharge the cloud and lightning activity diminishes





The August 21 Glow



Finding Best Fit

Spectra

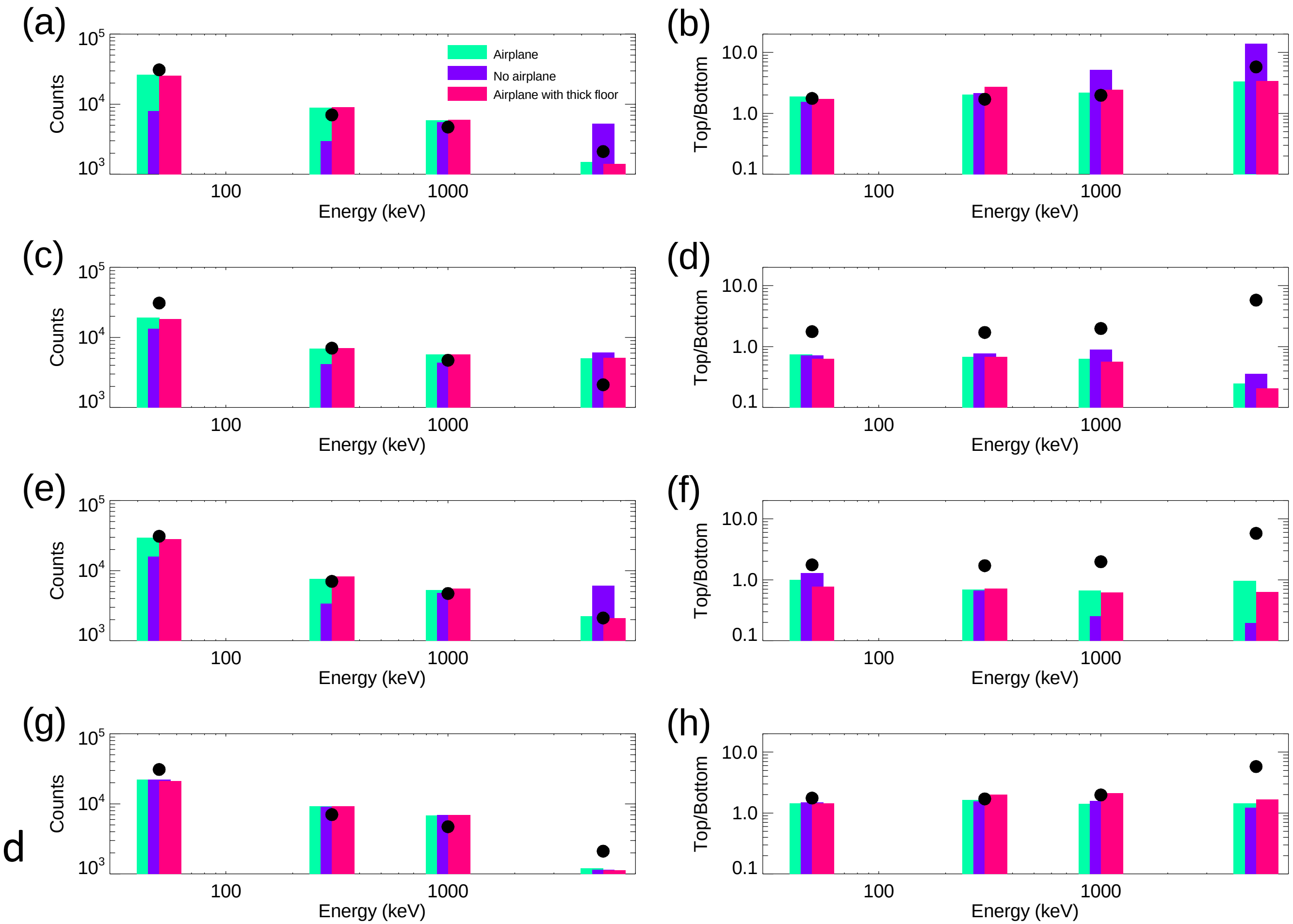
Top/Bottom Ratios

14 km down

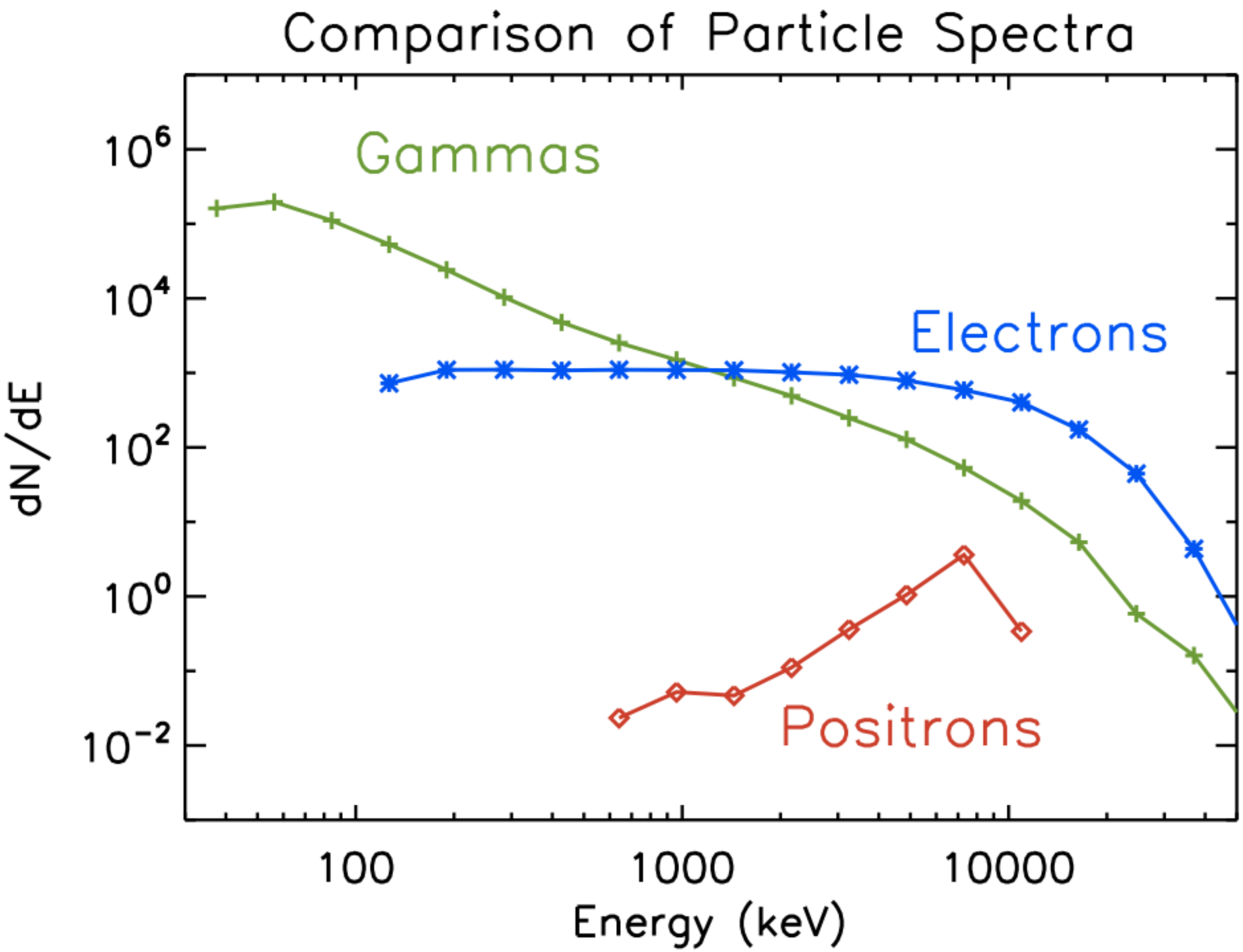
12 km down

16 km up

16 km down
Non-physical
Gamma-dominated



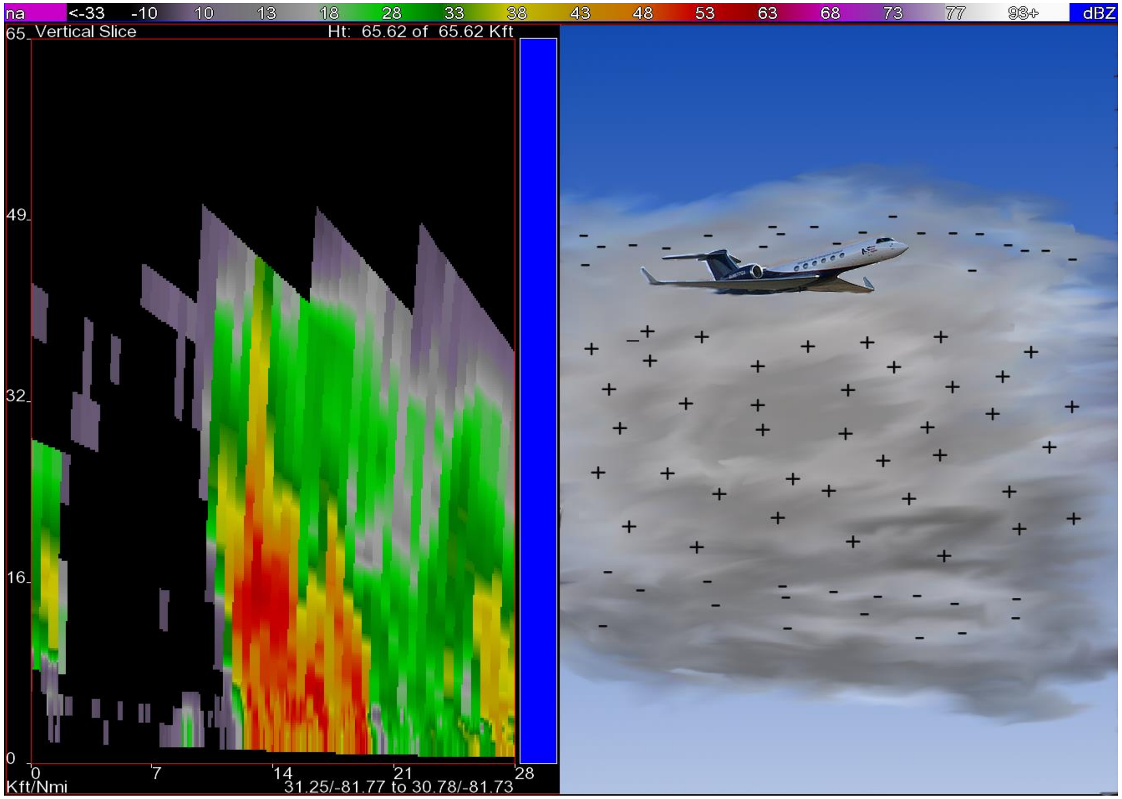
RREA at 14 km



Comparison of Particle Spectra
Gammas
Electrons
Positrons
10^6
10^4
10^2
10^0
10^-2
dN/dE
100
1000
10000
Energy (keV)

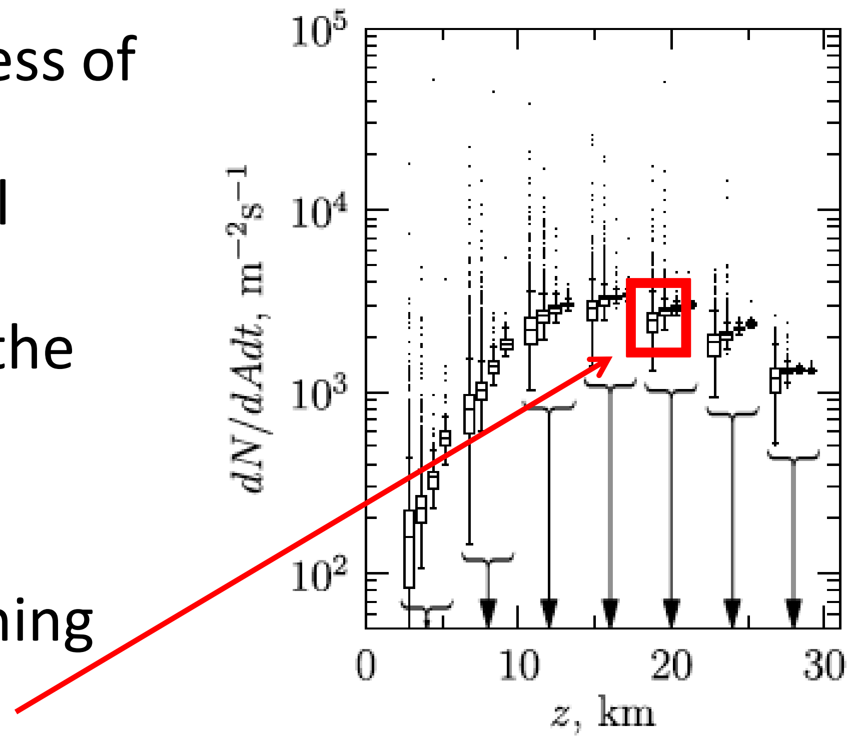
Best Fit Model

- In the end of a downward facing avalanche- directly being hit by electrons, positrons and gammas
- Consistent with flying between upper positive and negative screening layer



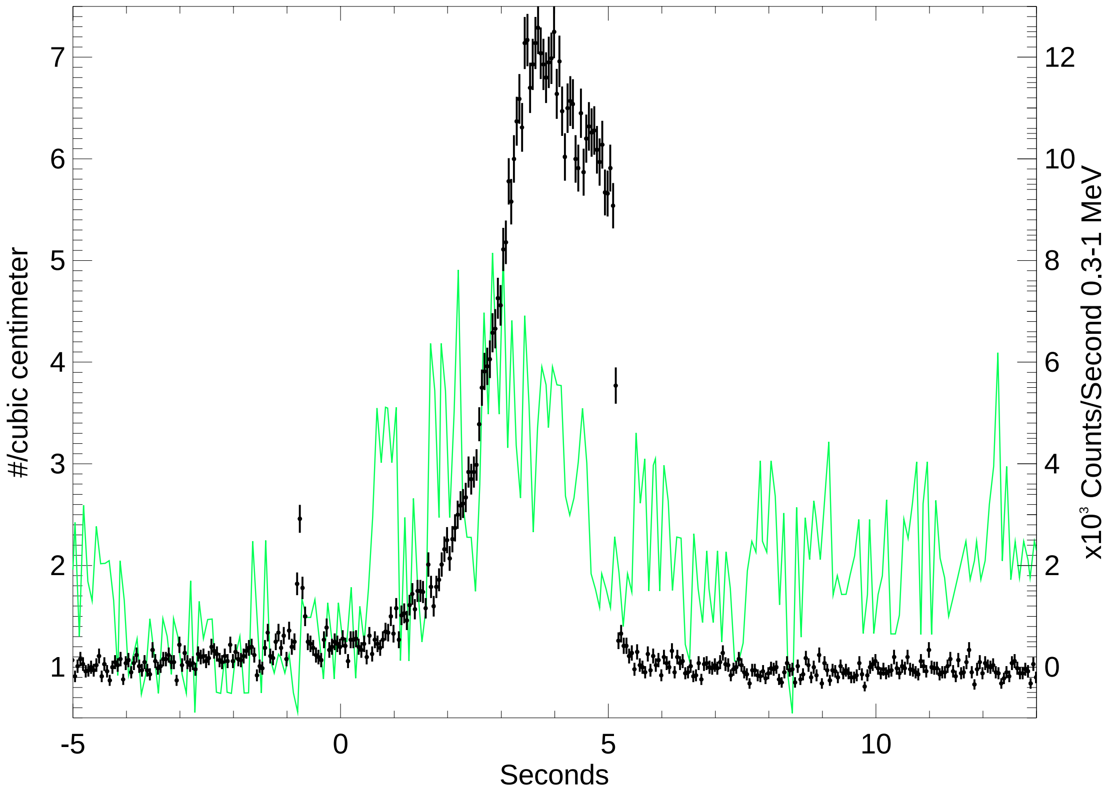
Avalanche Multiplication

- Avalanche multiplication is necessary to achieve brightness of Aug 21 glow
- Electric field approaches level necessary for feedback
- At the end of the avalanche, the electron fluence is 1181.71 electrons/cm^2/s
- Carlson et al. shows 0.25 electrons/cm^2/s at the beginning of the avalanche
- Multiplication factor of 4475, feedback dominates at 5000



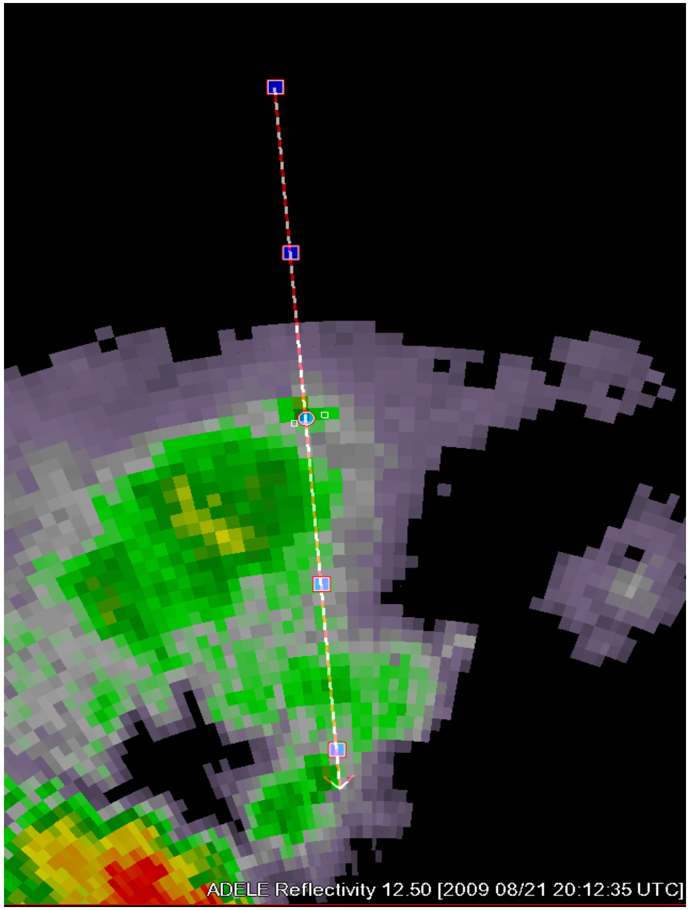
Number of 1 MeV seed electrons from cosmic rays
From Carlson et al. 2008
JGR, Vol. 113

Glows and Cloud Microphysics

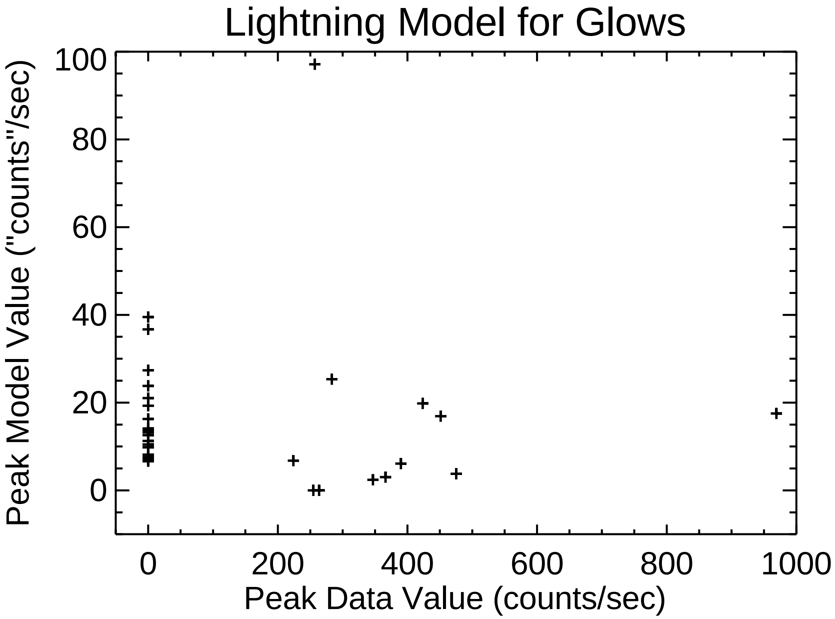


Light green – small ice as measured by NCAR’s Cloud Droplet Probe
Dark green - 300 keV-1 MeV gamma ray counts

Area/Duty Cycle of Glow



6.42 km^2 and 25.67 km^2 from radar echo
~1 km^2 from gamma and ice data



11/149 times ADELE is near active cell, glow is observed.
Lower limit: 8% of cells are glowing

Glows as Competition for Lightning

We can compute the discharge rate caused by the glow:

$$J = 2e\lambda_{cl}\alpha F_{re}$$

130 nA/m^2

Lower limit of current moved by glow: 9.62 mA, 60 mA, and 270 mA
Upper limit of current moved by glow: 126 mA, 811 mA, and 3.33 A

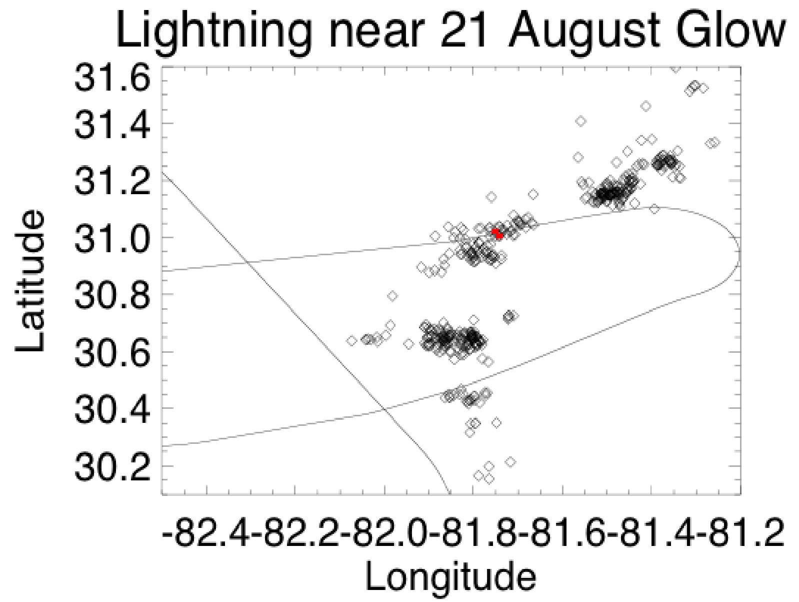
15 –CG flashes detected with USPLN, guess +IC flashes in cells.

1. $$\frac{N_g}{N_c + N_g} = 0.1 + 0.25\sin(\lambda)$$ (Pierce 1970)

Current is: 0.5 mA, 3.5 mA, and 14 mA

2. $$\frac{N_c}{N_g} = 4.16 + 2.16 * \cos(3\lambda)$$ (Prentice and Mackerras 1977)

Current is: 0.7 mA, 4.2 mA, and 16.9 mA

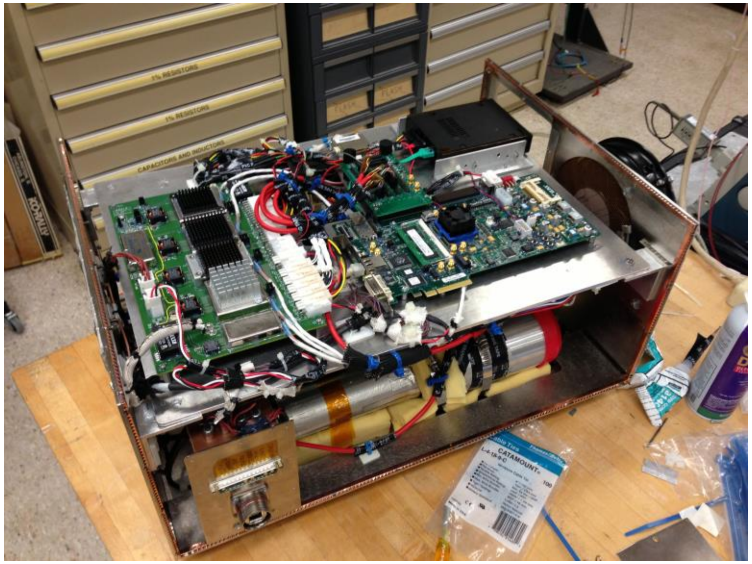


Outstanding Questions

- How bright/weak can glows/TGFs be?
- How often do they occur?
- How energetic can these phenomena be?
- Do TGFs follow RREA or AGILE deviation?
- Do TGFs have time structure? Are they an enhancement of x-ray stepped leaders?

ADELE Instrument – Version 2.0

- 5X5” plastic, 1X1” plastic, 3X3” LaBr
- Enclosed computer, FPGA, electronics
- 1 sensor head, fully autonomous



New Instruments/Campaigns

- Sub-μs time resolution
- Energy range to cover 100 keV-40 MeV
- Cheap, easily reproducible
- Gamma-ray Observations During Overhead Thunderstorms (GODOT) to be placed in Japanese winter thunderstorms starting now
- ADELE will be at CN Tower in late summer, Sierra Negra, Mexico in spring/early summer

Conclusion

- Portable instrumentation is very successful at measuring high-energy atmospheric physics
- Gamma ray glows are common
- Glows discharge thunderclouds substantial amount, may compete with lightning
- Glows can approach levels where feedback dominates….TGF occurs?

Thank you!

Questions?