Gamma Rays from Lightning

David M. Smith, Brian Grefenstette, Jacob Stanley,
SCIPP, U. C. Santa Cruz
Liliana I. Lopez, SFSU
Robert P. Lin, U. C. Berkeley
Christopher P. Barrington-Leigh, U. British Columbia

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1) Overview and physics of upper-atmospheric electricity

2) Introduction to TGFs

3) RHESSI evidence for thundercloud origin of TGFs

4) Broader significance and future projects

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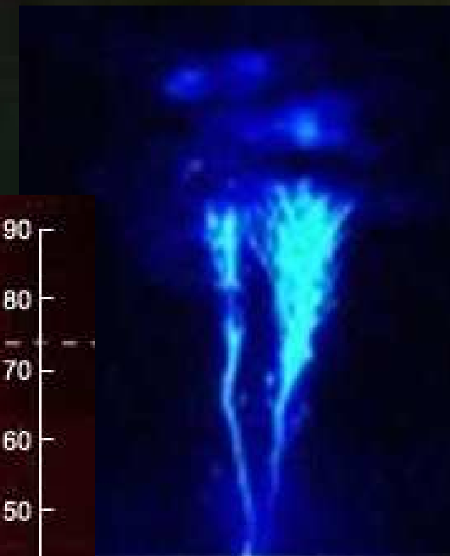
Classes of upper atmospheric phenomena associated with thunderstorms & individual lightning flashes:

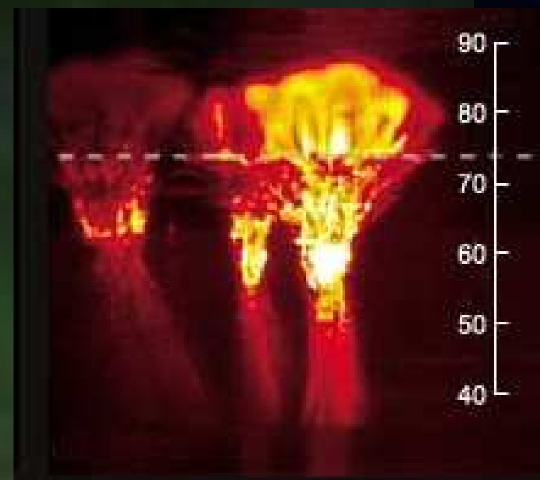
Red sprites, sprite halos, blue jets:

From just above thunderclouds (blue jets) to edge of ionosphere (sprites); Observed for decades, studied scientifically since ~1990.

Colors depend on density of air vs. altitude via collisional disruption of ionization states



V. Pasko



H. Stenbaek-Nielsen

Elves:

Expanding ring (or disk?) at ~90km (base of ionosphere): more common

Terrestrial Gamma-ray Flashes:

~1ms flashes of keV to MeV photons seen from space

Classes of air breakdown (in decreasing order of required electric field):

Conventional:

Any free electron gains enough energy between collisions to ionize the next atom it hits

Streamer Propagation:

Self-sustaining propagation: charge separation at tip creates local electric field high enough to create conventional breakdown

Relativistic runaway:

Seed electrons at high energy encounter less resistance; if they create more of their kind at each collision, avalanche occurs at lower E. Cosmic rays provide seeds (only need 1!)

Leader process:

High currents create local ionization at propagation tip by heating (propagation of lightning to the ground)

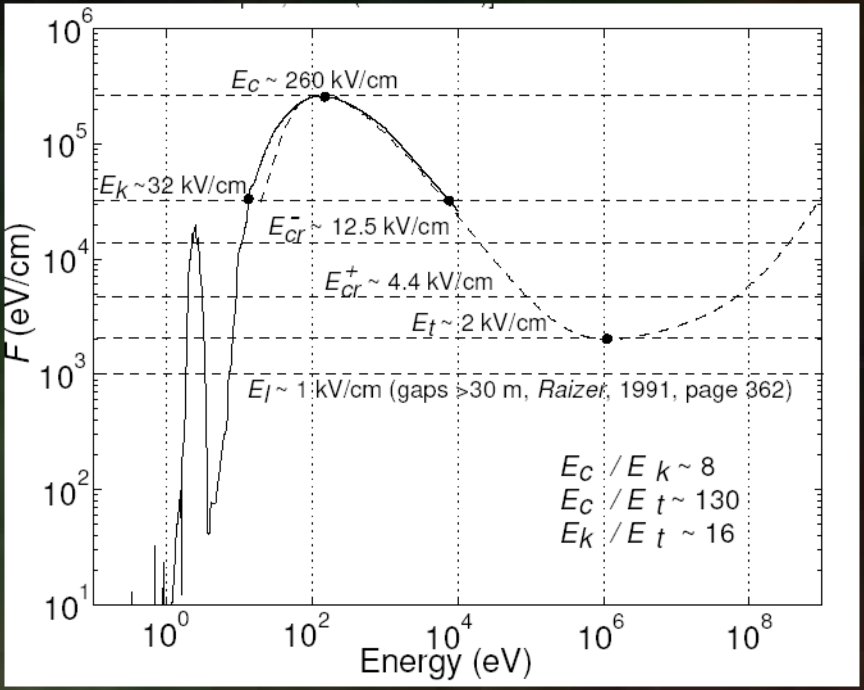


Figure by V. Pasko, from tutorial at the NATO summer institute on Sprites, etc., Corte, Corsica, 2004

Cloud-to-ground lighting leaves a charge on top of thunderclouds, "parallel plate capacitor" to the conductive ionosphere.

In the upper atmosphere, thunderstorm electric fields drop with altitude, but density drops faster --> a threshold altitude for the various processes:

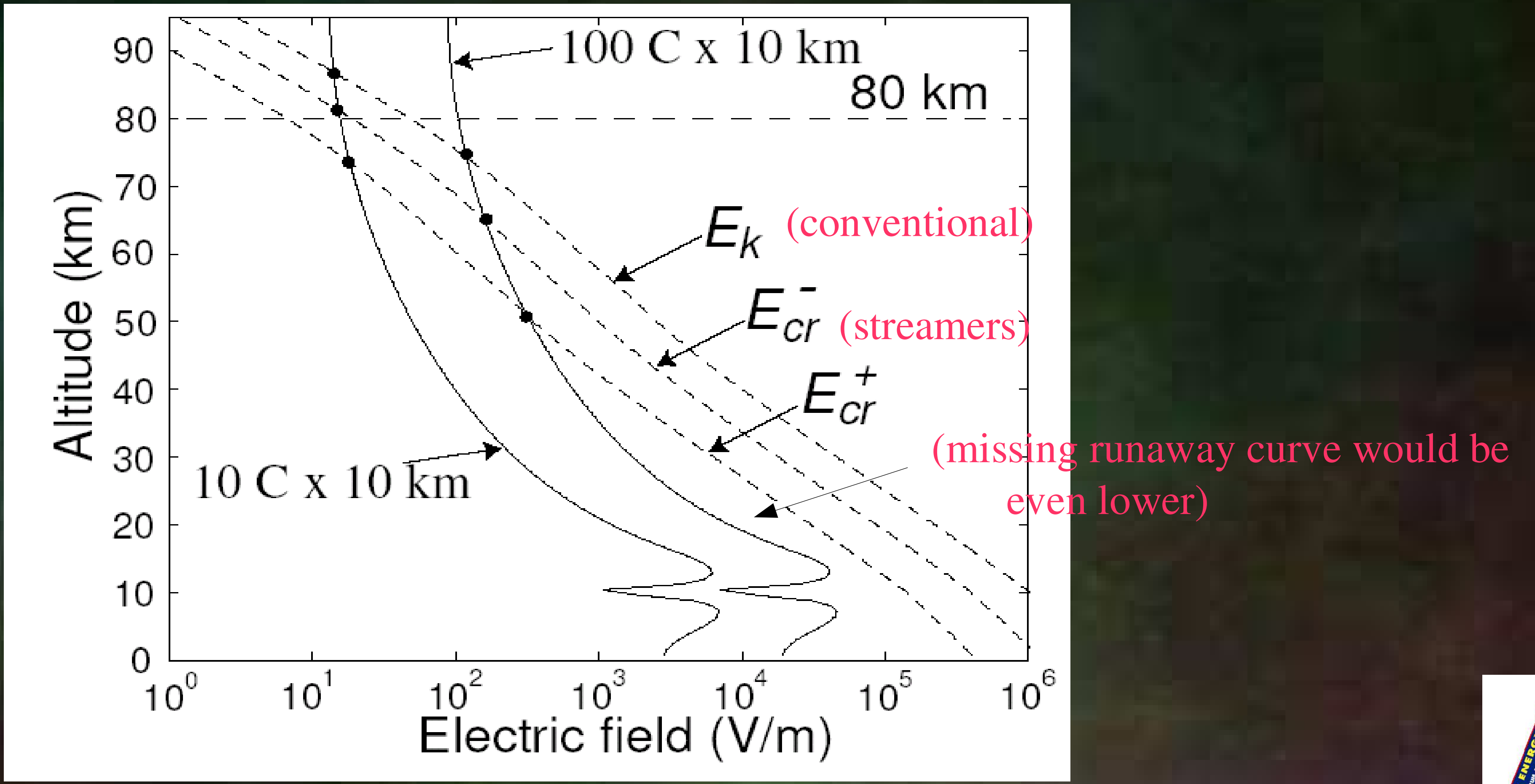


Figure by V. Pasko, ibid.

Probable sources of different phenomena:

DC electric field (possibly either polarity):

Sprites, blue jets

DC electric field (? +CG only ?): TGFs

→ Need large charge moment change

Transient E-field from EMP: Elves

→ Need large peak current

Observed signals:

Optical (from ground, airplanes, space)

VLF/ELF sferics (global range!)

Infrasound (sprites)

[Do TGFs imply any of the other phenomena are occurring at the same time?]

Role of the magnetic field in runaway avalanche:

Electrons will experience **ExB** drift rather than acceleration due to entrainment by the magnetic field, unless there is a sufficient rate of collisions to disrupt cyclotron motion.

At mid-latitudes, where there is a significant parallel component of **E**, acceleration is possible up to the ionosphere (Lehtinen, Bell & Inan 1999) . At the magnetic equator, it will be cut off when electrons are magnetized.

The altitude of magnetization has been estimated at
25-30 km (Babich et al. 2001) but also at
15-20 km (Sharma, Guzdar and Milikh 2004),
who suggest that a whistler-wave instability produces ducts that transport the e- to higher altitudes.

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Discovery of TGFs by BATSE on CGRO:

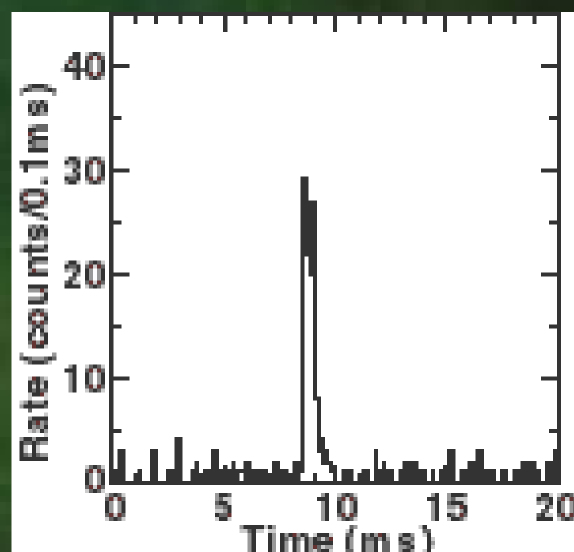
Flashes of duration ~ 1 ms

75 events discovered over 9 years

Hard spectra up to energies >> 300 keV

Correlation with thunderstorms

Photo credit: NASA



from Fishman et al.
(*Science*, 1994)

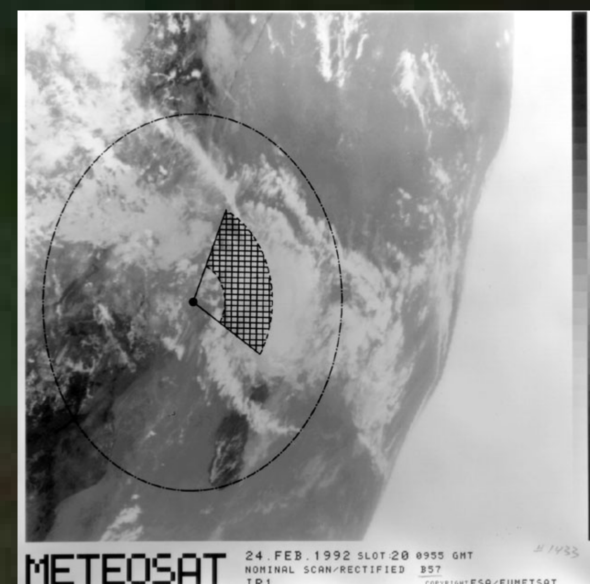
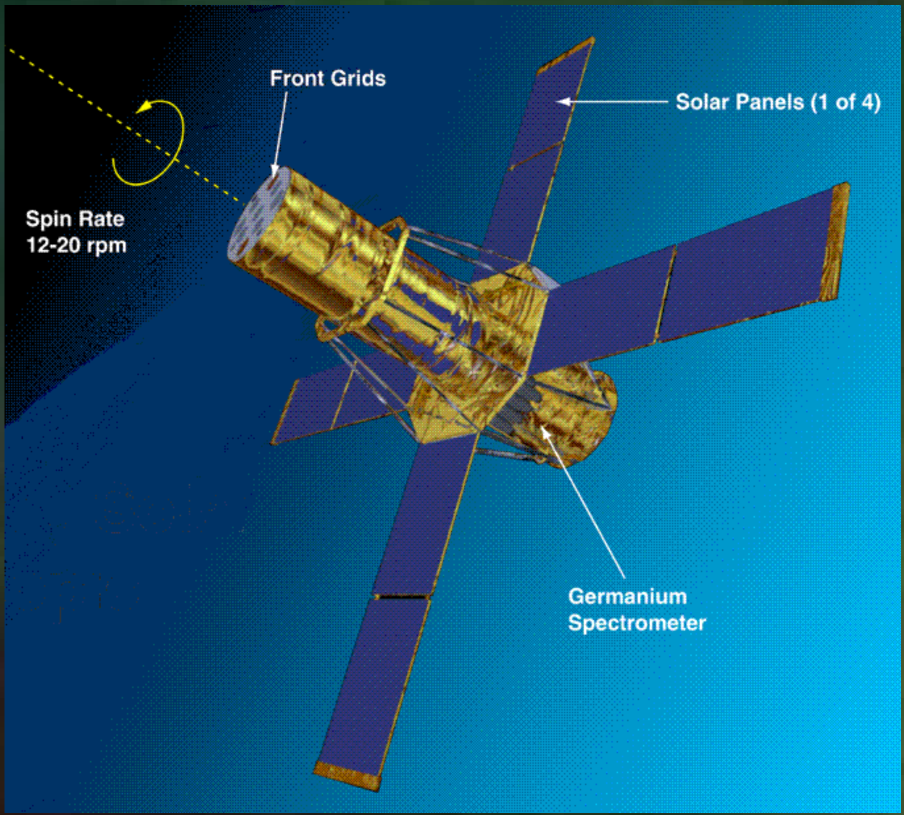


Photo credit: ESA

The Reuven Ramaty High Energy Solar Spectroscopic Imager

NASA Small Explorer spacecraft, 38 degrees LEO
Launched February 12, 2002 to study solar flares
Detectors smaller than BATSE's, but:



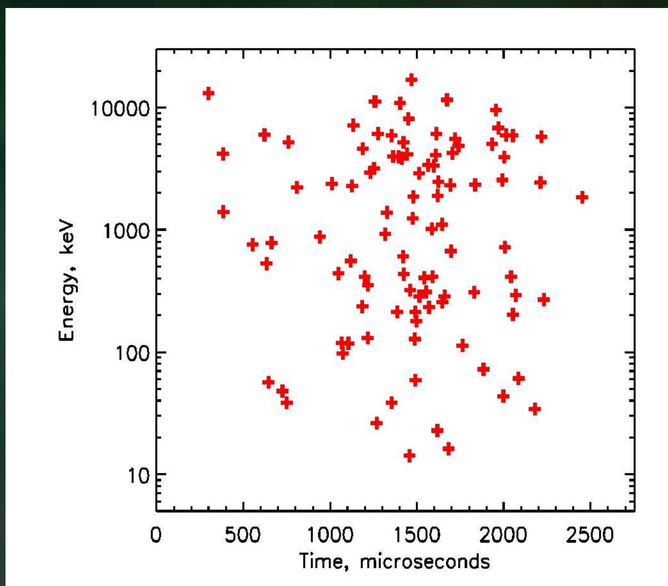
better high-energy response

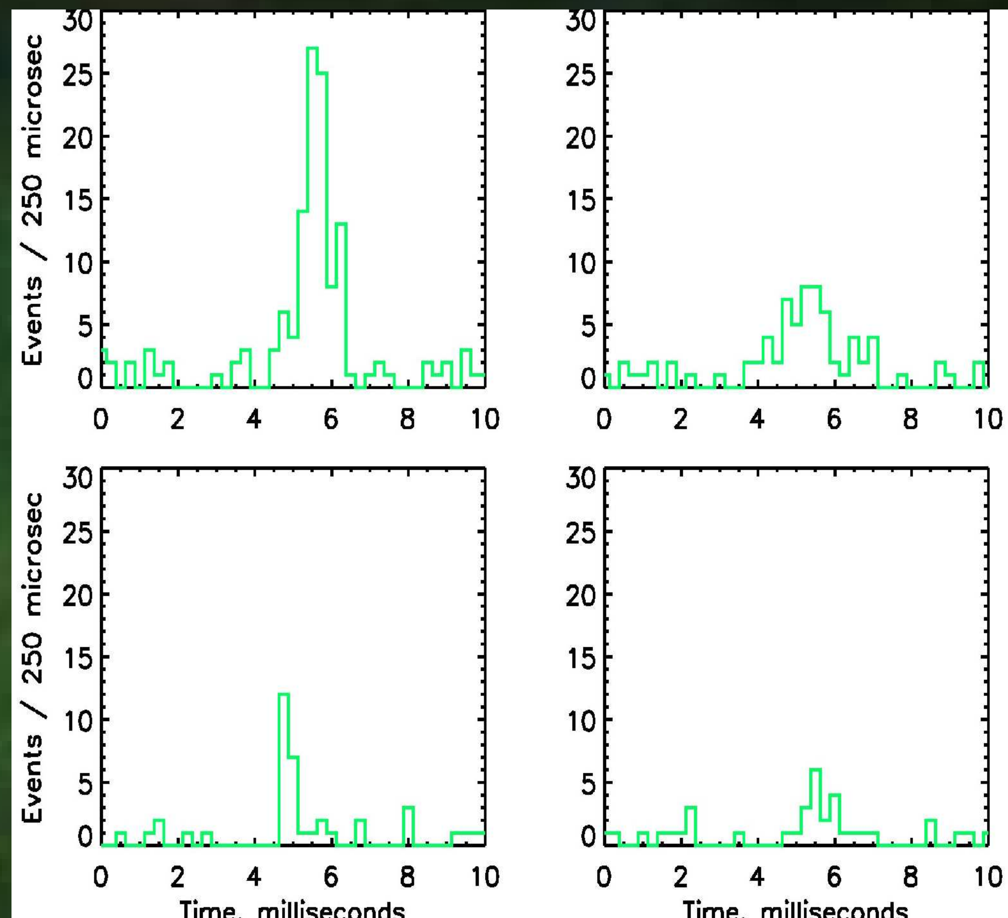
high energy resolution

no onboard trigger required
to recover events

RHESSI TGFs: Lightcurves

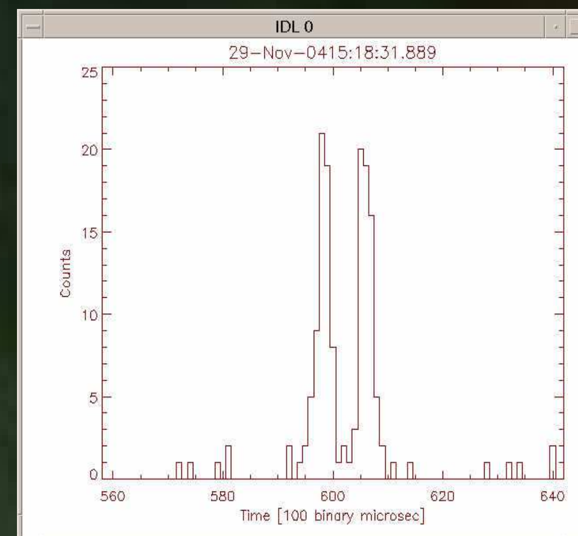
Durations from 200 us to 3.5 ms; consistent with BATSE, shorter than most TLEs.

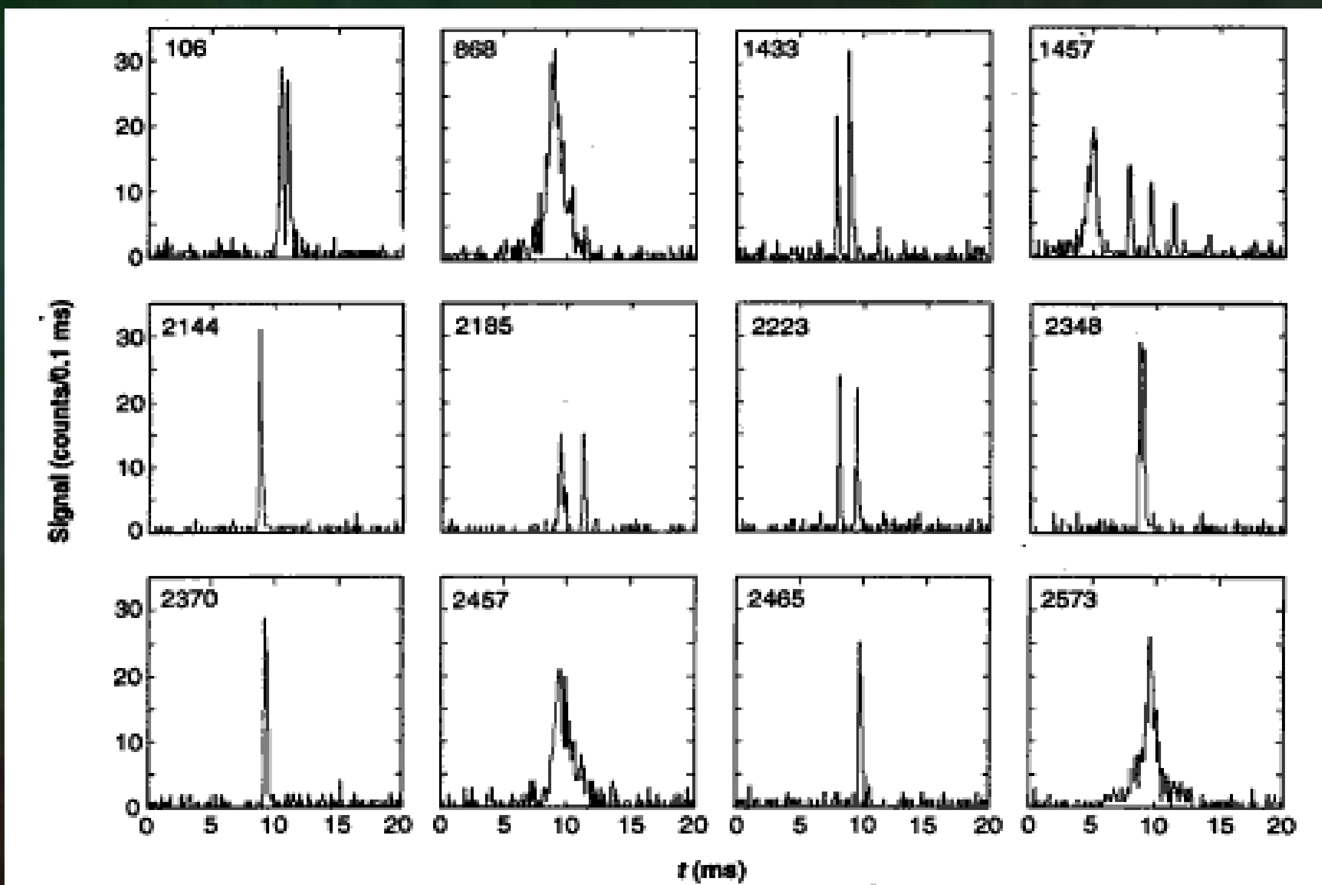




RHESSI has seldom seen BATSE's multiple flashes:

Multiple flashes were about 30% of BATSE's database, but rarely seen by RHESSI; attributable to BATSE's 64ms trigger window, which would be biased strongly in their favor. They are probably closer to 1% of the true total.

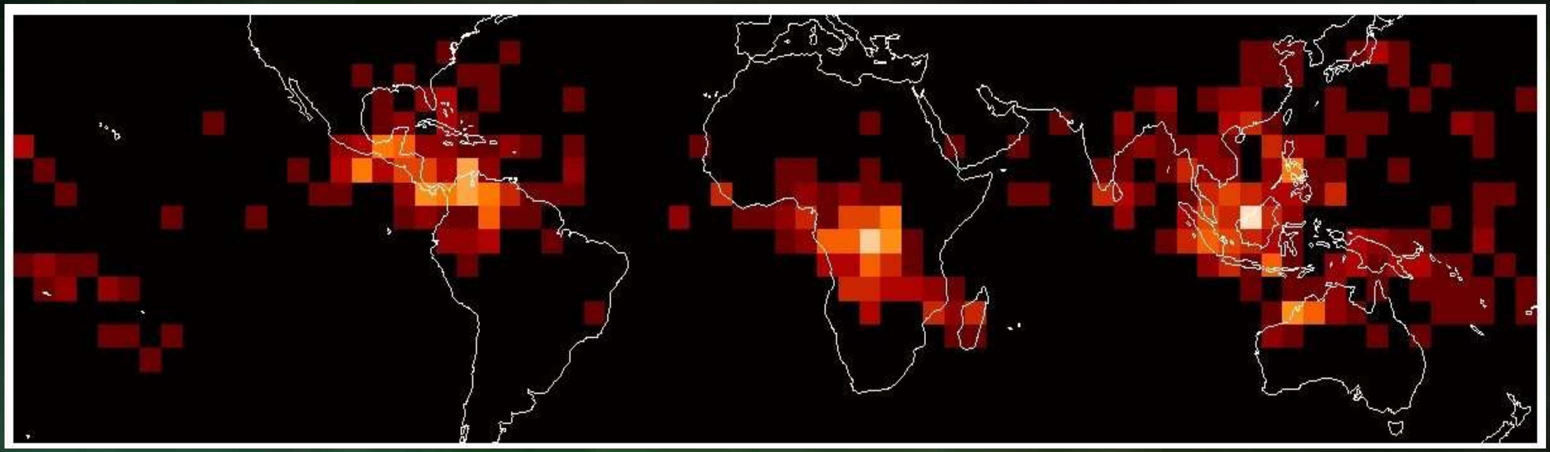


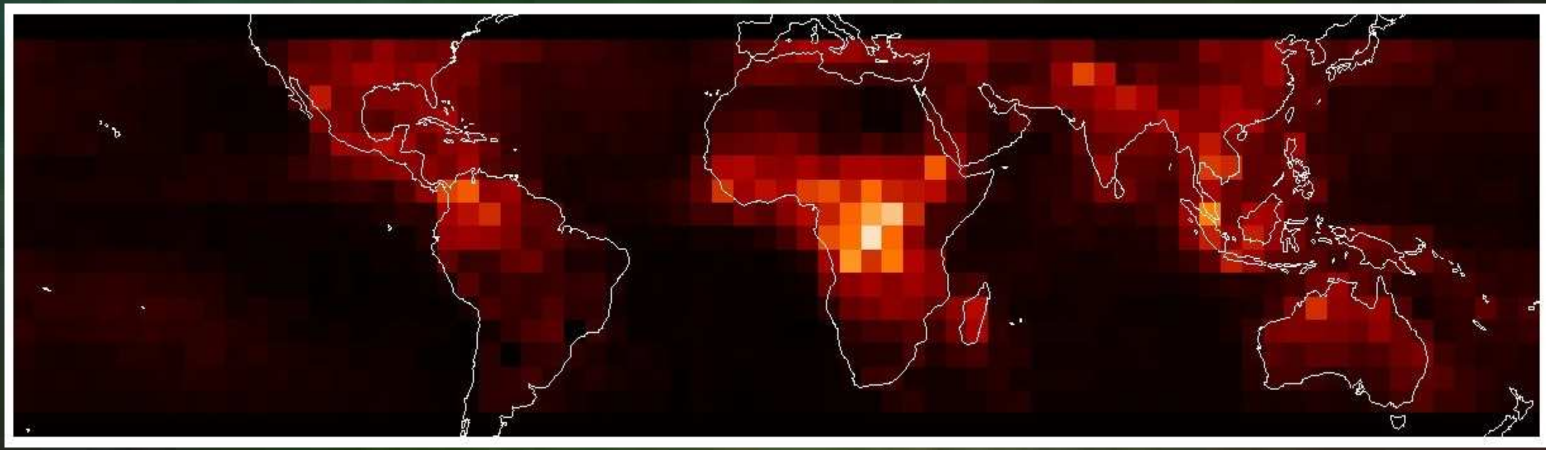


From Fishman et al. 1994, *Science*

Mid-latitude/temperate regions with a lot of thunderstorms, good satellite coverage, and many sprites show no TGFs

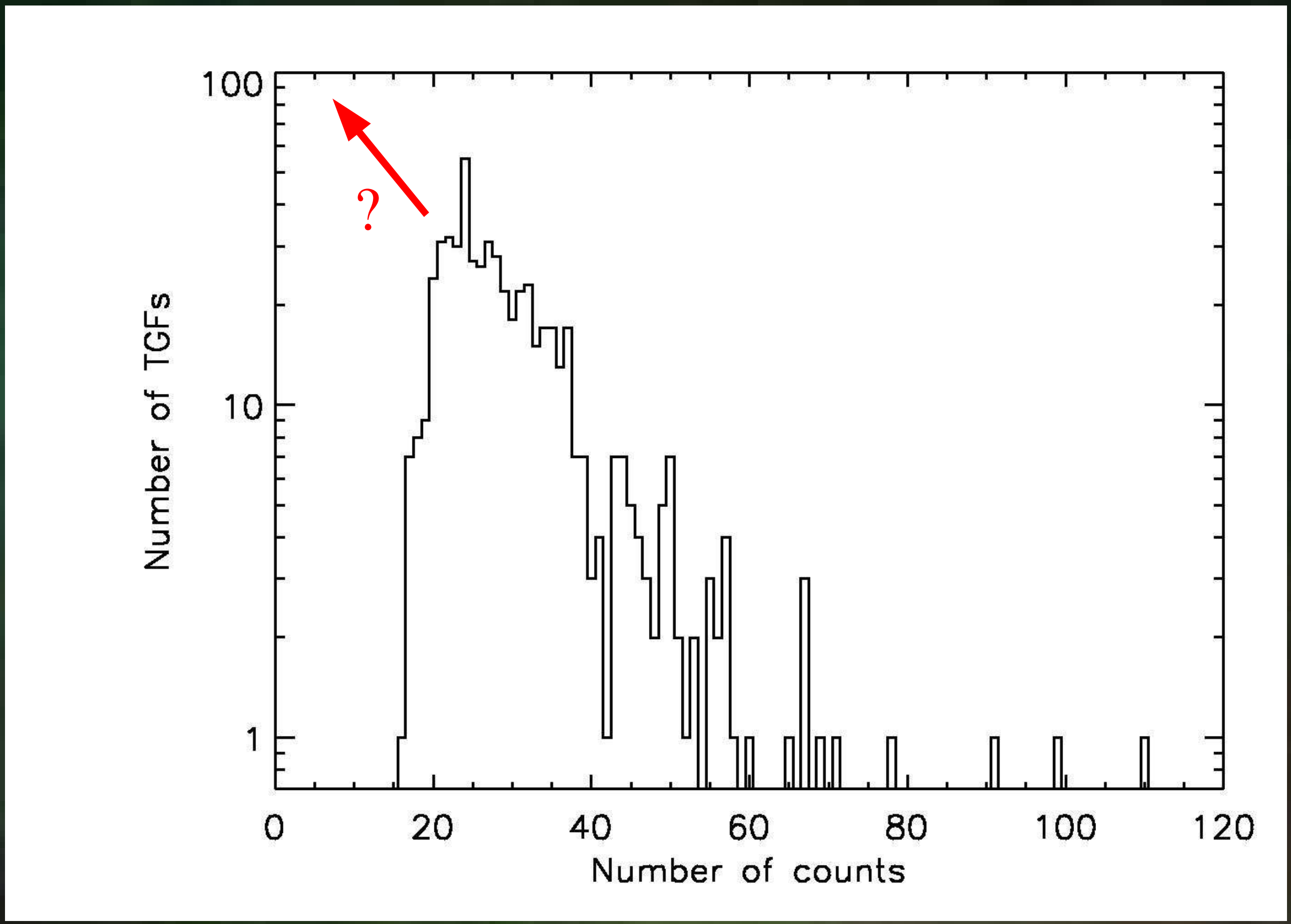
TGF map:





Lightning Map from NASA LIS/OTD science team, Multiplied by RHESSI global coverage/response function

Brightness distribution cuts off sharply around RHESSI's sensitivity limit for our triggering algorithm; is this the tip of the iceberg?



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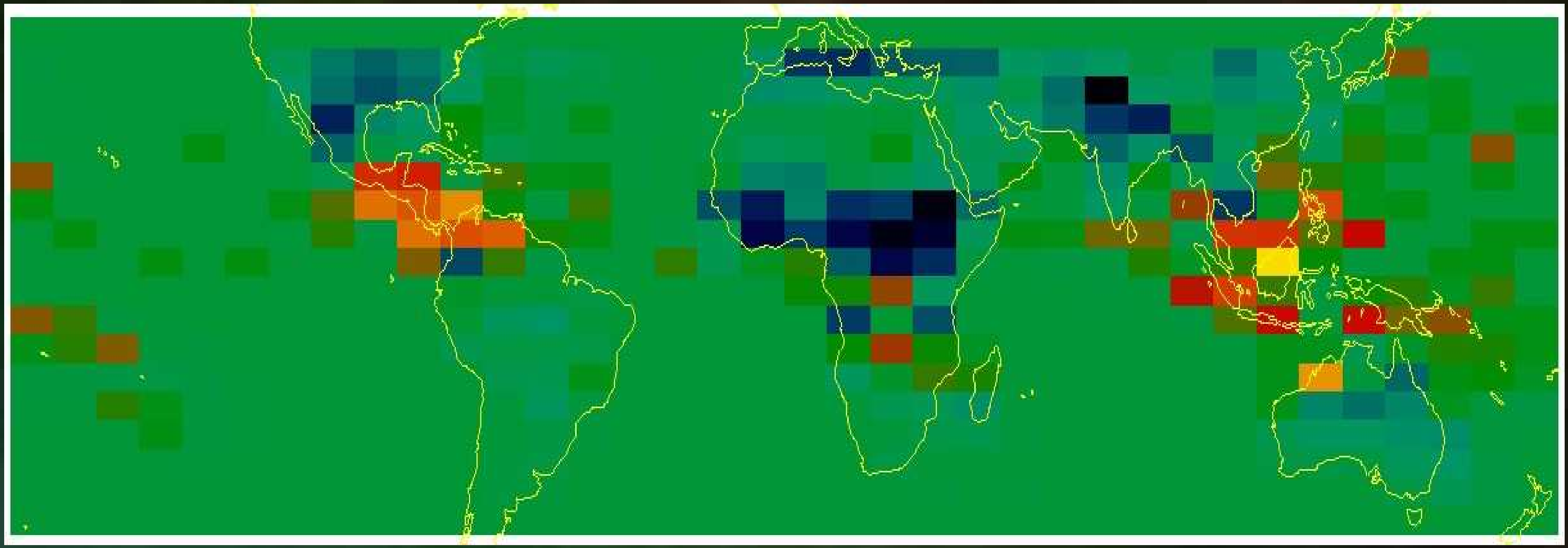
Difference map shows Africa and temperate zones less efficient at TGFs.



Deficit at higher latitudes explains USA, Mediterranean, Delhi

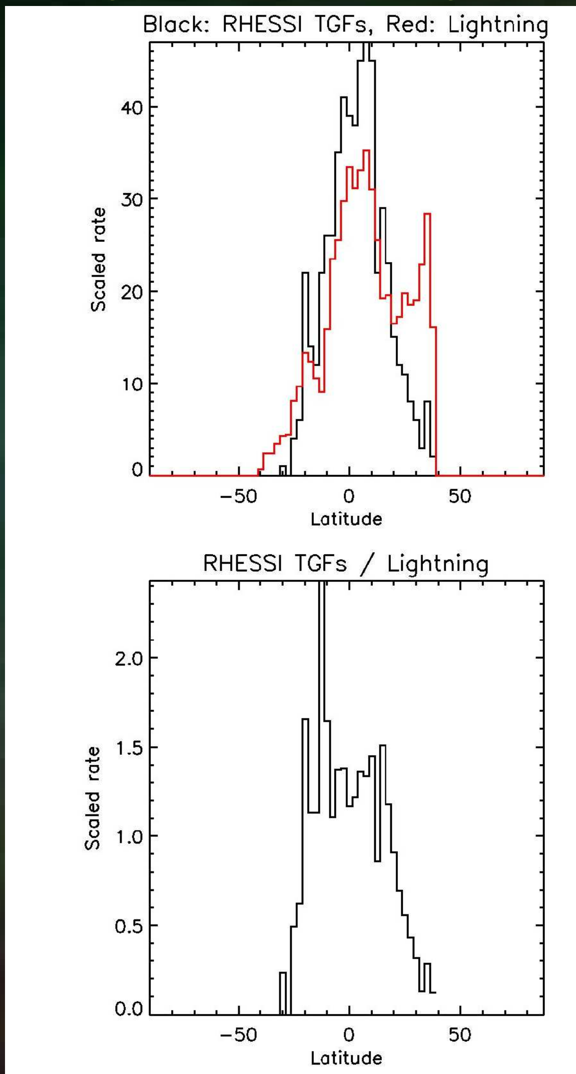
Deficit over land explains USA, Delhi, Central Africa

land vs. ocean TGFs show no difference except mean local time
(land prefers dusk; ocean is equally dusk and predawn/dawn)

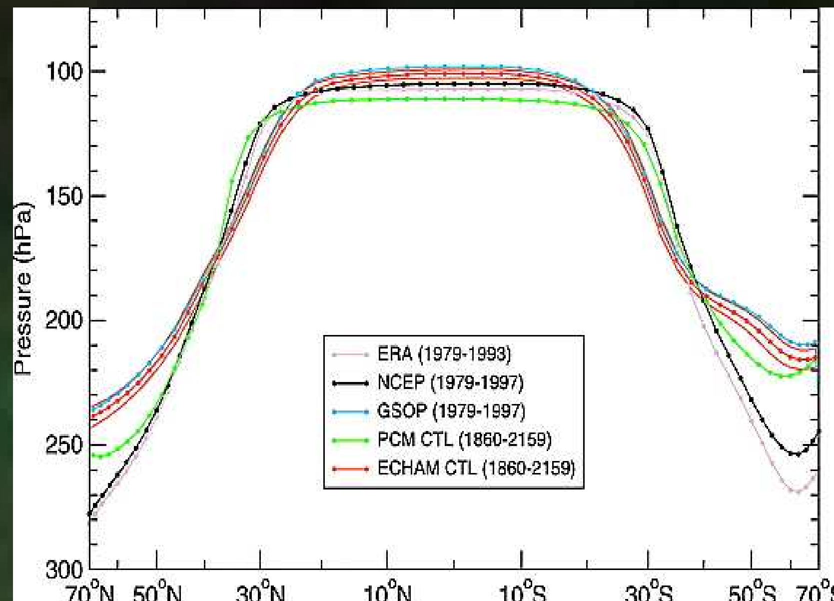
What about differences in lightning between the LIS/OTD epoch and the RHESSI epoch?

The TGF/lightning ratio vs. latitude is consistent with a dropoff as soon as the tropopause starts to lower, suggesting production at high cloud tops (see E. Williams et al., in press)

Integrate over longitude:



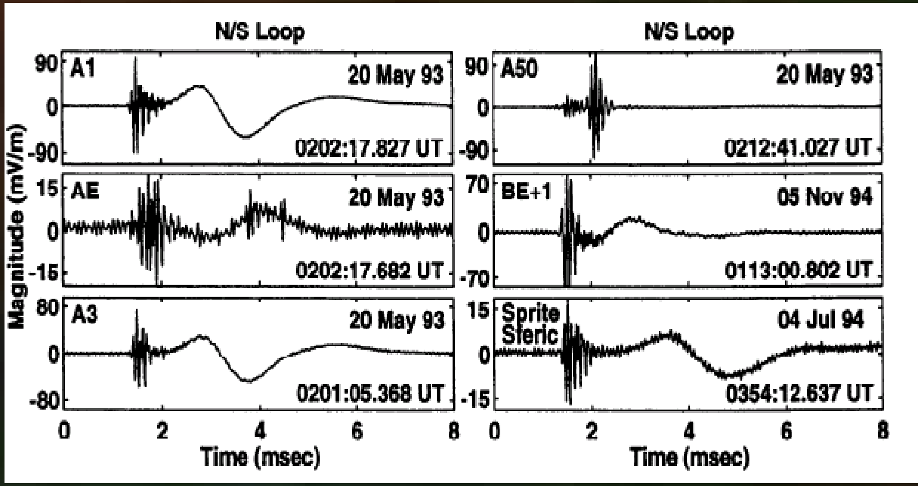
?



Atmospheric pressure at the tropopause vs. latitude for several published models (from B. D. Santer et al. 2002, JGR)

This suggests the TGFs we **do** see are highly diminished by atmospheric absorption

One BATSE TGF, early on, unequivocally associated with a VLF/ELF sferic similar to those that make sprites
(Inan et al. 1996, GRL 23, 1017)



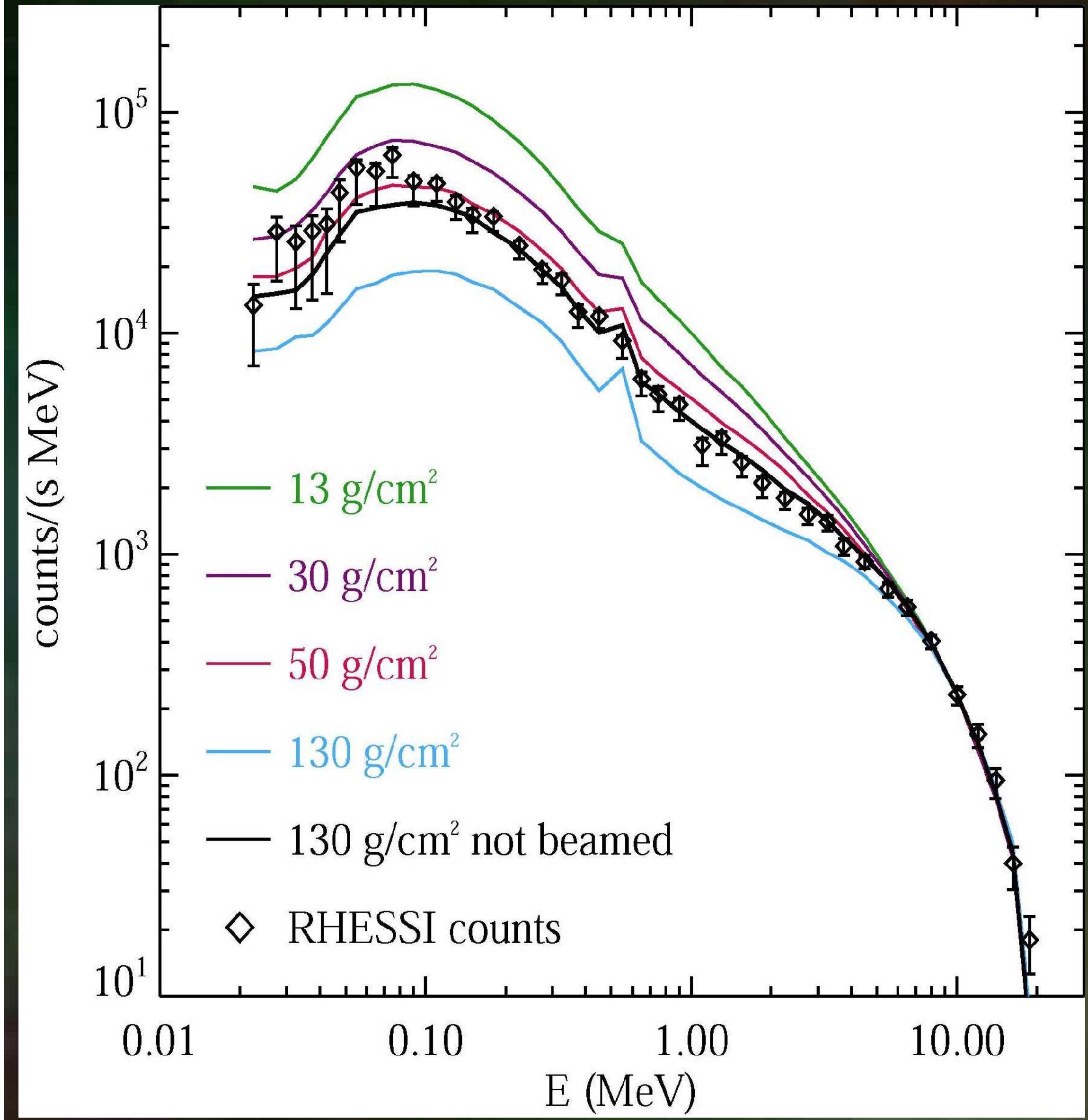
Cummer et al. (2005, GRL) find that a sample of RHESSI TGFs are either coincident with a small sferic or none at all.

Therefore, most TGFs are created when ***E*** at sprite altitudes is extremely small, and can't initiate relativistic runaway breakdown;

Therefore, the breakdown must take place close to the region of charge separation, probably in or just above the thundercloud.

IF *the breakdown is caused by a DC field; but see also new models by Inan, Lehtinen et al.*

RHESSI TGFs: Spectrum



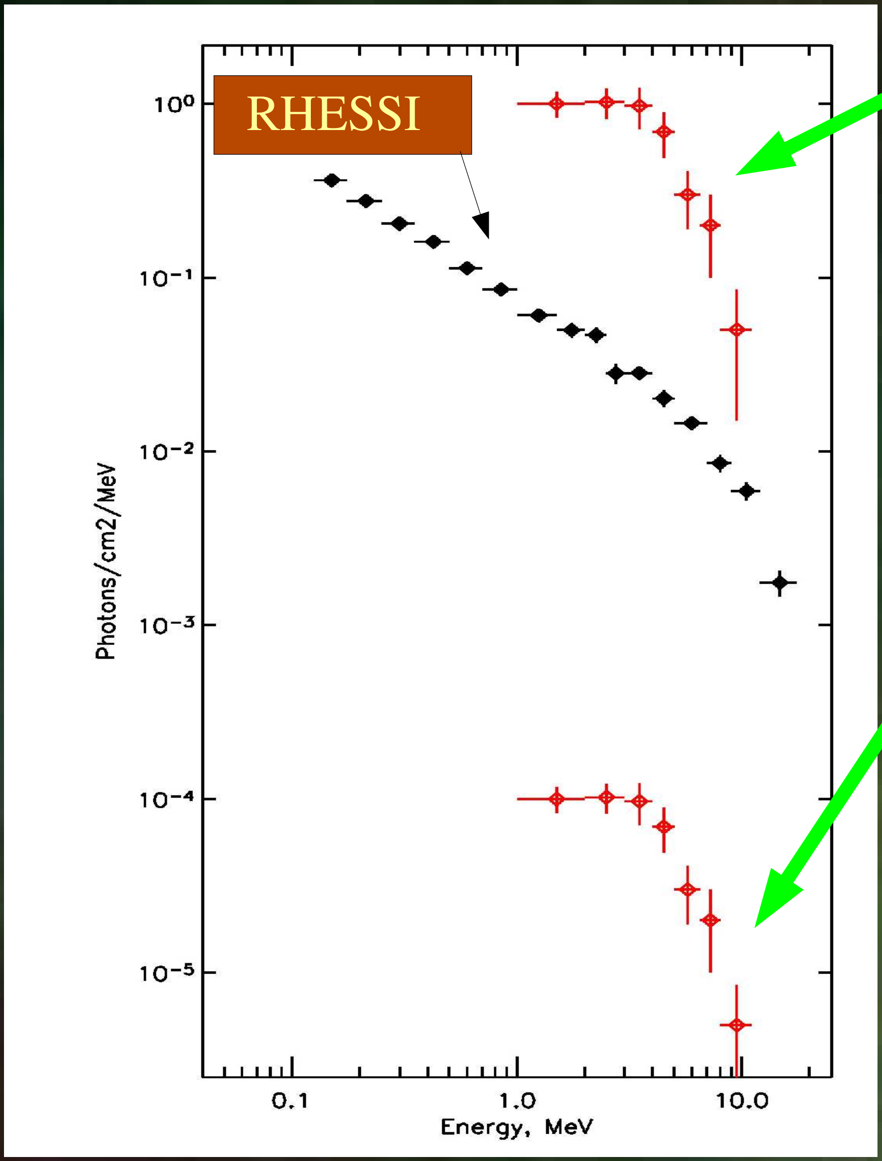
Summed spectrum of 289 TGFs

Spectra tend to be similar from event to event, but slightly more variation than chance

Models are relativistic runaway breakdown simulation by J. Dwyer.

Unabsorbed bremsstrahlung **must** be steeper than E^{-1} around 1 MeV; spectrum requires > 50 g/cm^2 of intervening air (Dwyer & Smith 2005, in press)

Observation of gamma-rays on the ground from a process probably in a thundercloud (Dwyer et al. 2004) demonstrates low-energy absorption due to high atmospheric depth.



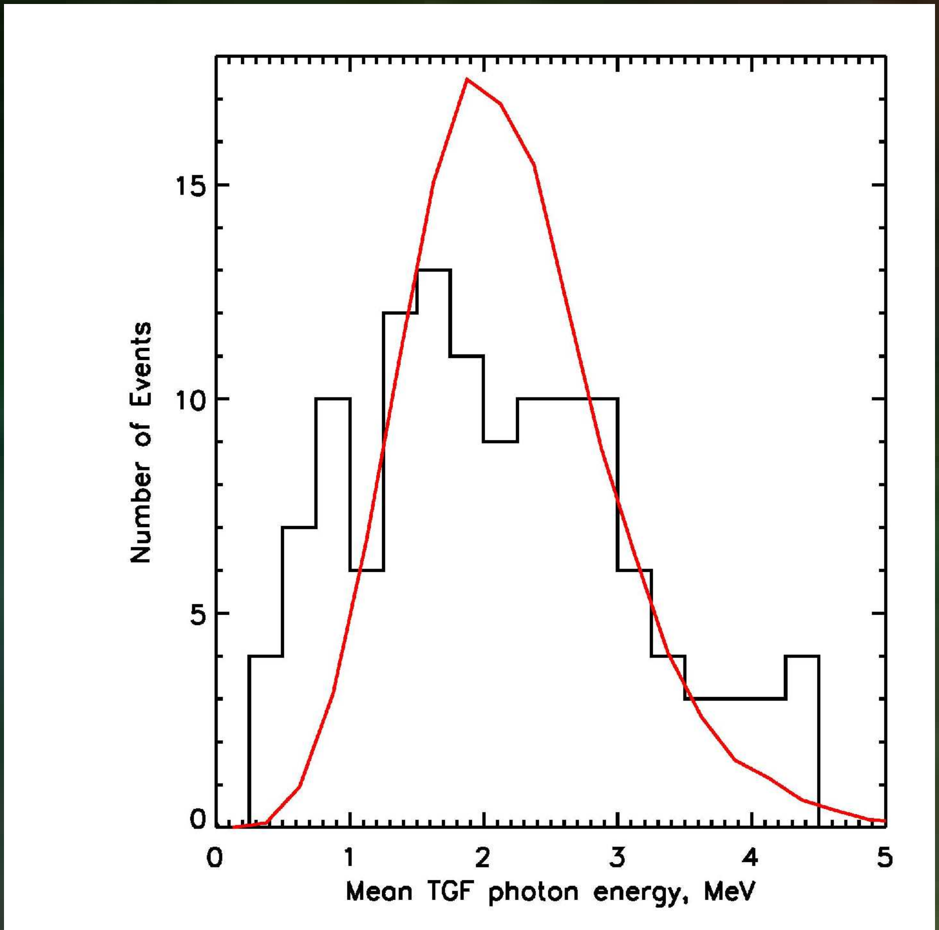
Dwyer et al. 2004 seen from the ground, estimated altitude 6-8 km

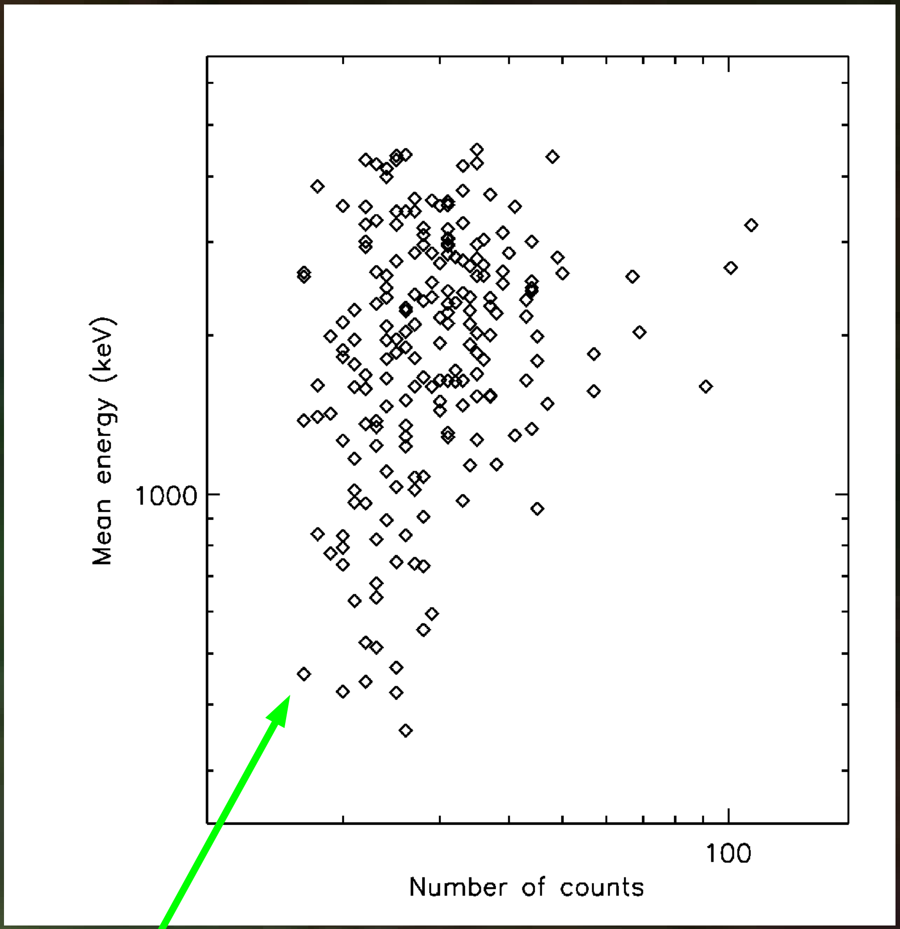
Dwyer et al. 2004 scaled to 600 km distance, same absorption column (approximately right*)

***BUT,** there is a factor of ~million absorption, so only a couple of km higher could make it **much** brighter.

Upshot: **could** be same events, but near top and bottom of cloud

Spectral variability?





Distribution of mean energies is broader than predicted for a uniform spectrum (red curve)

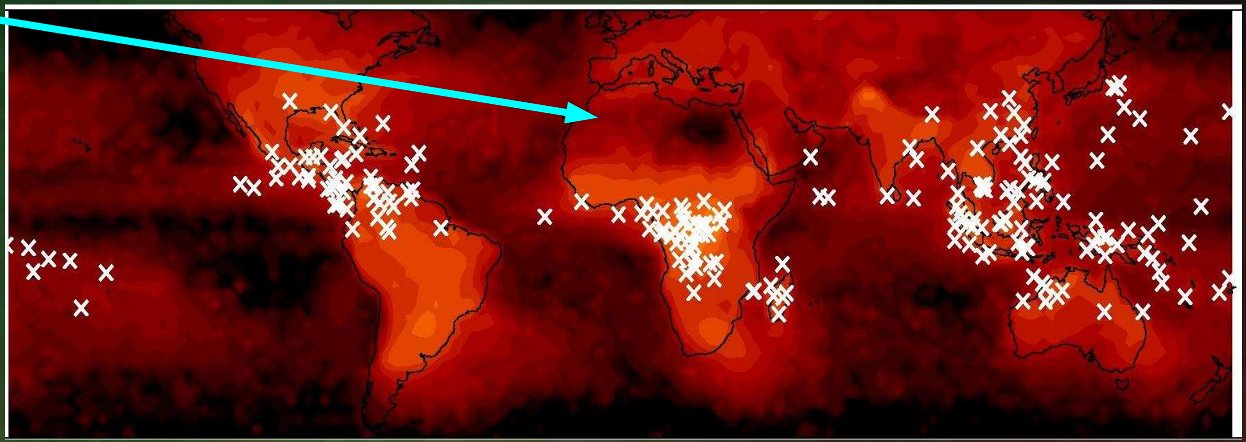
The low-energy population is also faint.

Faint, soft events, if a separate population, may be either

1) Viewed near the edge of the upward beam, or
only Compton-scattered photons (far off the edge), or

2) Due to acceleration at the magnetic conjugate point,
with the electrons entering the atmosphere
downwards.

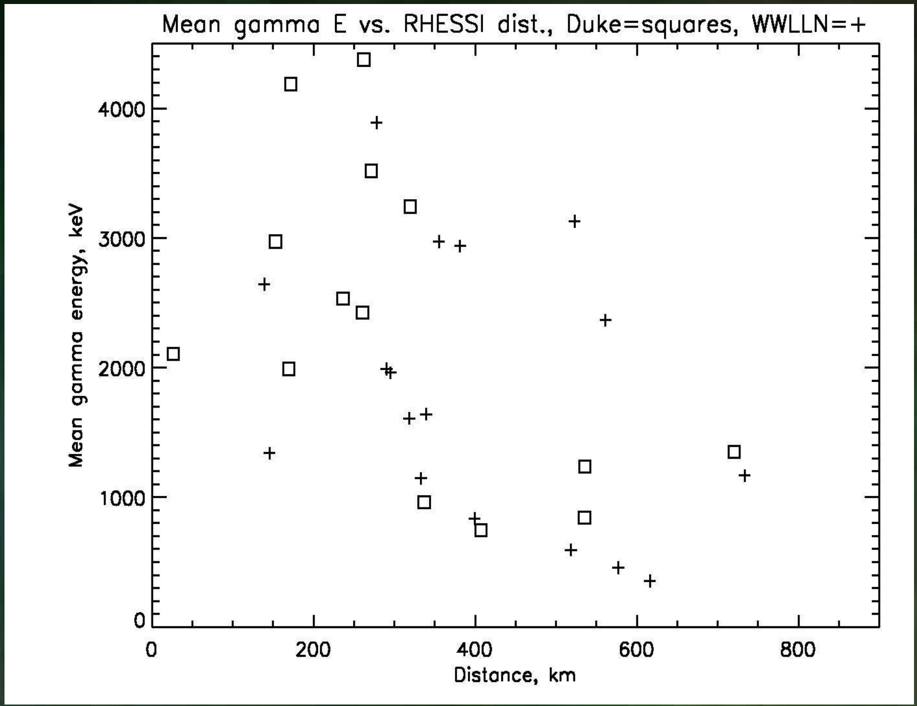
If we are seeing conjugate events, there should be many over the Sahara:

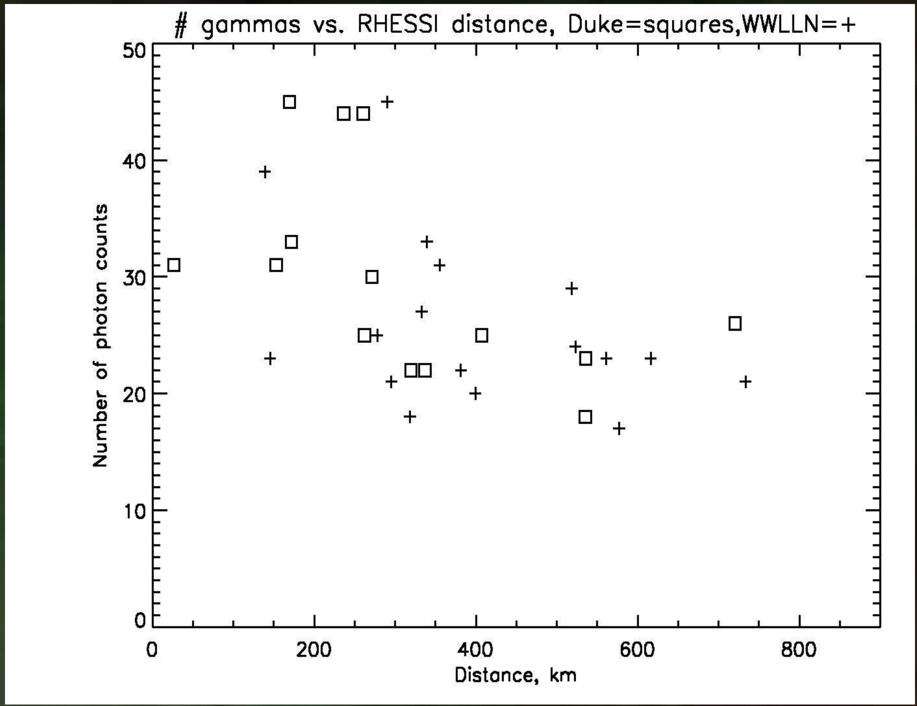


Radio "sferics" can be localized and the distance from the subsatellite point found

The softest events are all at large distances

The brightest events are all at small distances





Therefore off-beam or Comptonized viewing is a good interpretation for faint/soft events

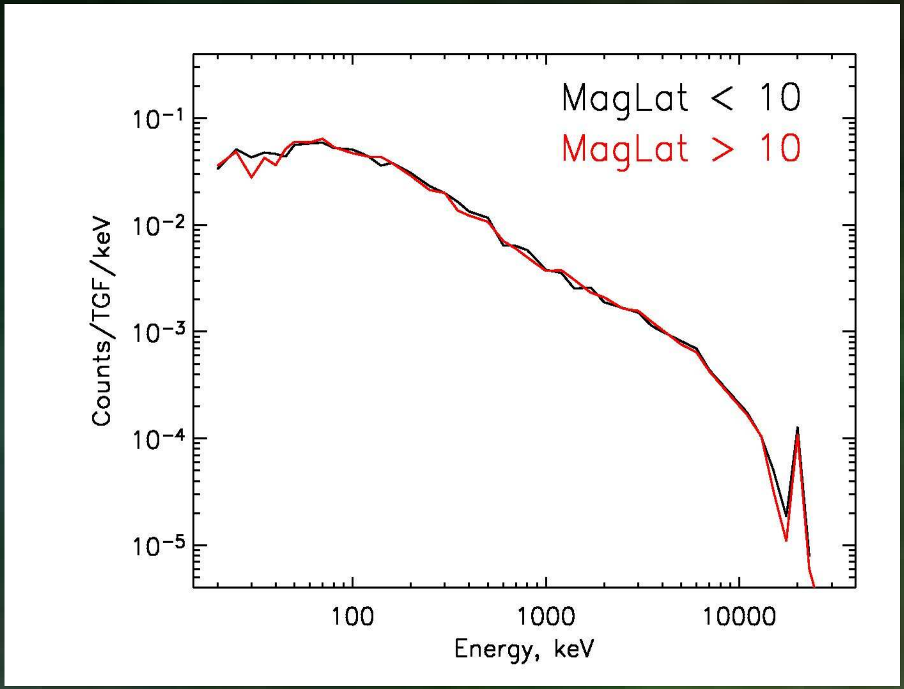
Therefore the variation in **intrinsic** brightness is less than the variation due to distance

Radio positions from S. Cummer, Duke U. (squares), R. Holzworth & E. Lay, UW (crosses)

The spectrum and intensity* are independent of magnetic latitude and local time:

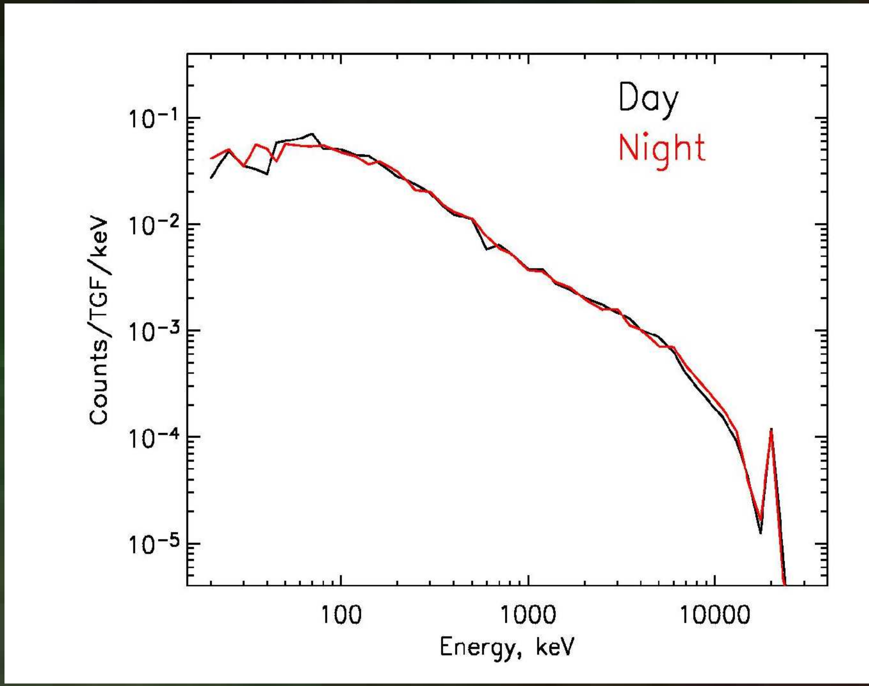
*subject to strong selection effects

Magnetic latitude



Suggests **deep** origin in atmosphere because magnetization of electrons doesn't seem to matter

Local time



Suggests **deep** origin in atmosphere because ionosphere has different heights during night and day

NEXT STEP:

Quantitative modeling of the expected dependences for beaming vs. Comptonization effects

Summary of arguments for a thundercloud origin (15 to 21 km) for RHESSI TGFs:

Map shows deficit at high latitudes consistent with production at tropopause (Williams)

Flat spectrum around 1 MeV demands strong atmospheric absorption (Dwyer)

Weak sferics show lightning cannot produce breakdown by DC field
at high altitudes (Cummer)

No weakening of TGFs near equator (no magnetization of electrons)

No weakening of TGFs during daylight (not accelerated up to ionosphere)

No sign yet of *faint* conjugate events over the Sahara
(Could be sensitivity issue)

But:

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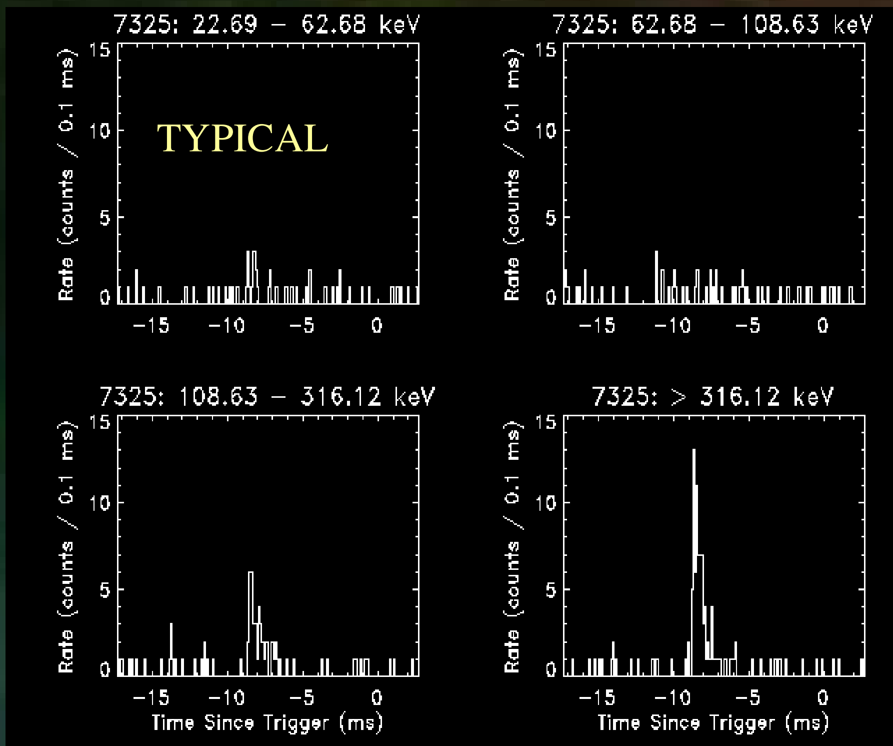
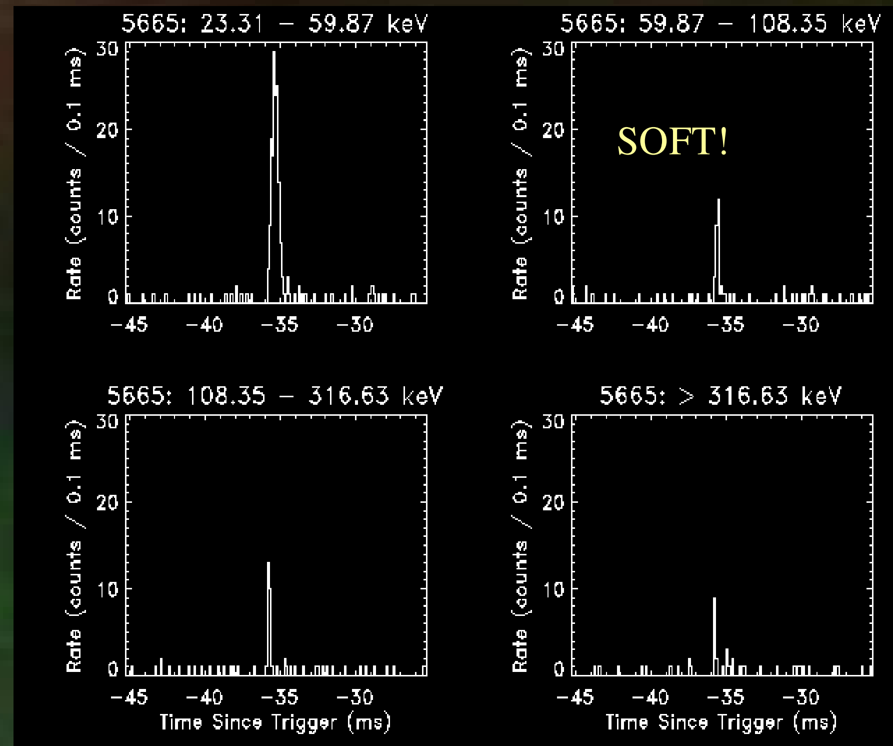
Certain BATSE TGFs are much softer than the norm.

None of these yet seen by RHESSI (sensitivity issue?)



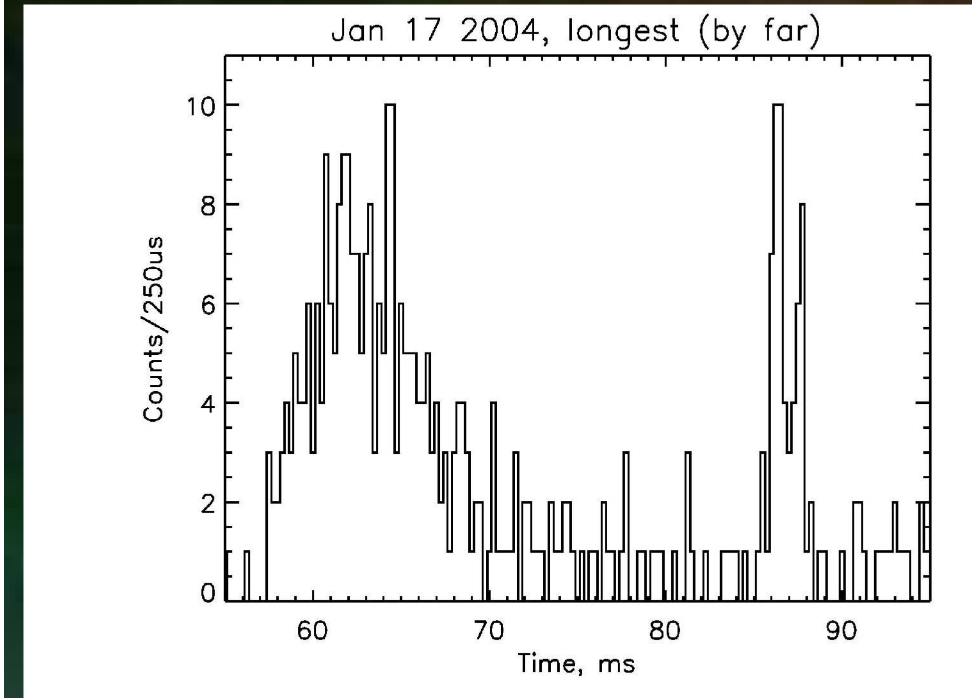


Data courtesy of the BATSE webpage at NASA/MSFC

Are there two kinds of TGF?

two acceleration regions within each?

conjugate events after all?

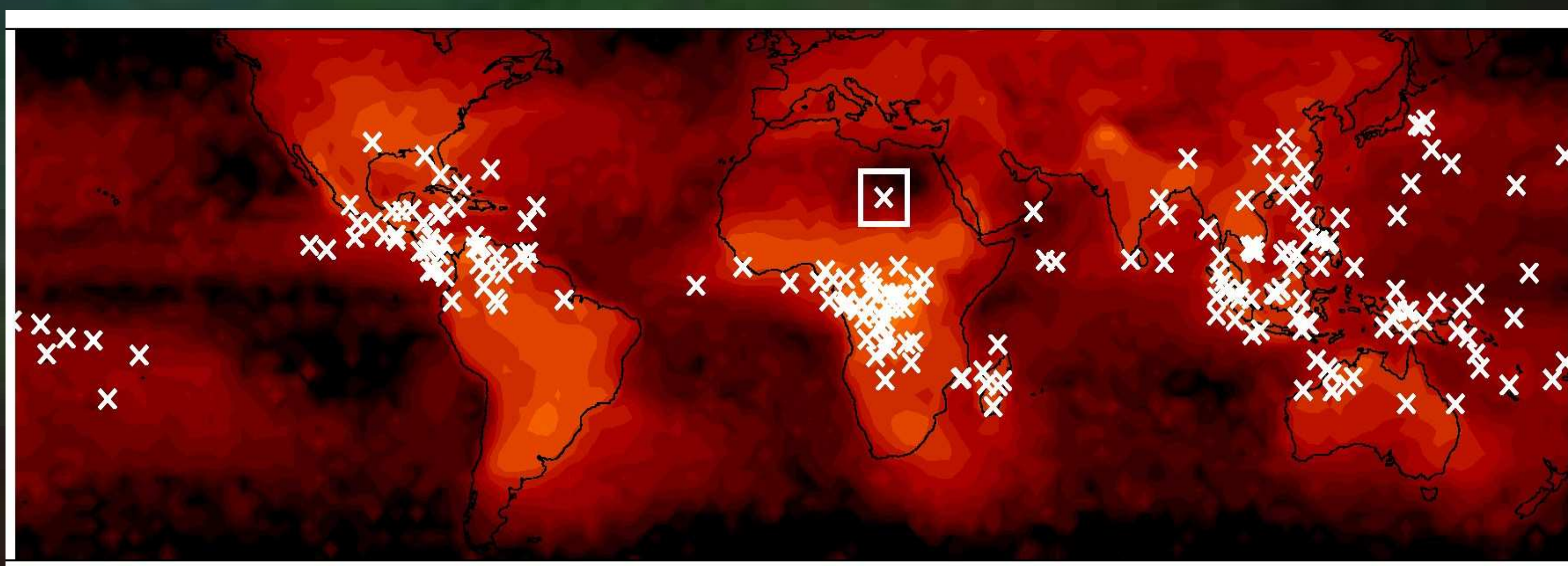


Jan 17 2004, 12:46:50.970

- Longest and brightest RHESSI TGF
- Northern Chad (Sahara). No storms here, but plenty of storms in January at the conjugate point.
- If every TGF has a conjugate flash, the first Sahara event we see should be faint, not bright! Unless.....

We got lucky and caught the e- beam directly with the spacecraft!

Currently looking for conjugate storms & sferics.



Greater relevance?

1) If TGFs occur in thunderclouds, is there a TGF associated with **every** lightning stroke? Is relativistic runaway the trigger for all lightning?

2) What is the total energetics of the TGF compared to other lightning processes? Is there chemically significant ionization at important altitudes for ozone (e.g. 30 km)?

3) Do escaping MeV electrons help populate the inner belt?

Rough estimate of number of monoenergetic 35 MeV electrons responsible for gamma rays:

Assume isotropic bremsstrahlung *
Assume thick target **
Assume no atmospheric loss of gammas ***
~ 3x10^15 electrons, or
~ 20 kJ (lightning is many MJ)

There **is** a population of > 10 MeV electrons in the inner belt (Galper et al. 1999, JGR); estimating the TGF contribution is TBD.

* Tends to overestimate the e- content compared to a beam
** Tends to underestimate the e- content compared to a thin target
*** Could underestimate by several orders of magnitude

What next? (I)

Is there a threshold, or are there many smaller events?
    -> More sensitivity

What are the soft events? Are there two breakdown regions?
    -> Better low-energy response (20-50 keV)

Is there a connection with optical phenomena: sprites, elves, blue jets, pixies.....?
    -> Joint optical observations

What next? (II)

TARANIS:

French microsatellite will carry gamma-ray detectors with area comparable to RHESSI but better low-E response, and downward looking cameras to detect sprites. SCIPP (Smith/Grefenstette/Stanley) is involved with the gamma-ray instrument design, which is being led by LANL.

CUAD:

SCIPP proposal currently under review at NSF to deploy new sprite cameras (UCSC) and VLF/ELF radio instrumentation (Duke) in the Caribbean for joint observations with TGFs from RHESSI and CORONAS-F (a Russian mission).

BALLOON OBSERVATIONS:

Proposal being prepared for NSF to fly small balloon payloads above thunderstorms and detect TGFs from 10 to 50 times closer.

For dessert:

Three TGFs observed during a single pass over a single storm: