On the Importance of Observing Radio Emissions Associated with Terrestrial Gamma-ray Flashes

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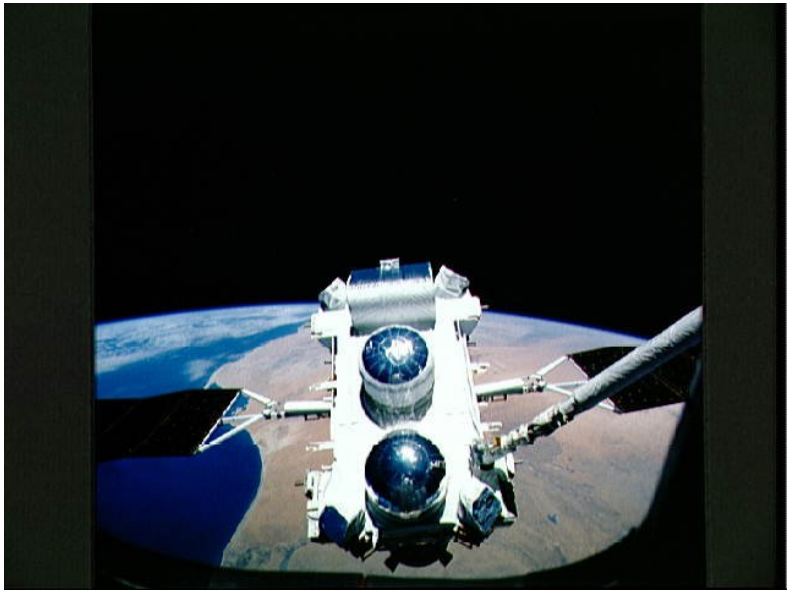
- The second of NASA's Great Observatories, the Compton Gamma Ray Observatory (CGRO), was launched on April 5, 1991 aboard the space shuttle Atlantis.
- Deorbited and re-entered the Earth's atmosphere on June 4, 2000.

CGRO is inspected by TRW workers prior to shipment to the Kennedy Space Center. CGRO was the heaviest astrophysical payload ever flown at the time of its launch. Credit: NASA.

- CGRO's mission: to observe celestial gamma-ray sources.
- CGRO had four instruments that covered an unprecedented six decades of the electromagnetic spectrum, from ∼20 keV to 30 GeV.



CGRO with its solar array panels deployed is grappled by the remote manipulator system (RMS) during STS-37 systems checkout. Credit: NASA.

- The Burst and Transient Source Experiment (BATSE) detector modules are located on the 8 corners of CGRO.

- From 1991 to 1994, BATSE had detected over 900 cosmic-ray bursts, several X-ray transients, and pulsed hard X-ray sources.
- Sources are located by comparing the relative response of the detectors, which view different directions.

Dr. Gerald Fishman of the Marshall Space Flight Center works on one of the Burst and Transient Source Experiment (BATSE) detector module. Credit: NASA.

- In May 1994, Dr. Fishman and collaborators report the discovery of unexplained gamma-ray flashes of atmospheric origin (>300 keV), that we know today as "Terrestrial Gamma-ray Flashes" (TGFs).
- The gamma-ray flashes are observed to be correlated with thunderstorm activity.

Discovery of Intense Gamma-Ray Flashes of Atmospheric Origin

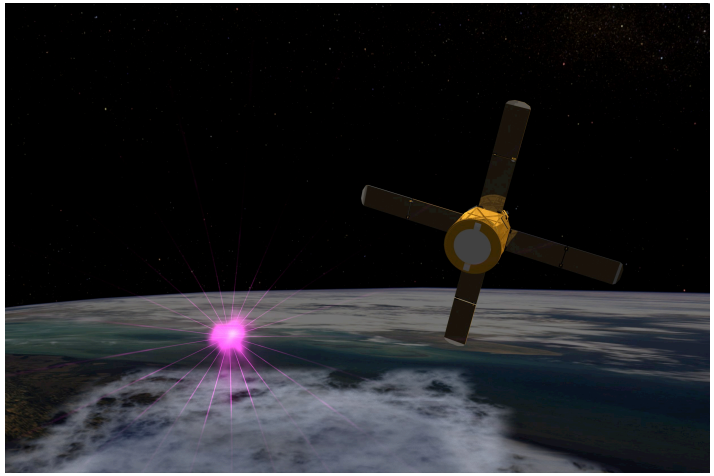
G. J. Fishman, P. N. Bhat,* R. Mallozzi, J. M. Horack, T. Koshut, C. Kouveliotou, G. N. Pendleton, C. A. Meegan, R. B. Wilson, W. S. Paciesas, S. J. Goodman, H. J. Christian

Detectors aboard the Compton Gamma Ray Observatory have observed an unexplained terrestrial phenomenon: brief, intense flashes of gamma rays. These flashes must originate in the atmosphere at altitudes above at least 30 kilometers in order to escape atmospheric absorption and reach the orbiting detectors. At least a dozen such events have been detected over the past 2 years. The photon spectra from the events are very hard (peaking in the high-energy portion of the spectrum) and are consistent with bremsstrahlung emission from energetic (million–electron volt) electrons. The most likely origin of these high-energy electrons, although speculative at this time, is a rare type of high-altitude electrical discharge above thunderstorm regions.

[*Fishman et al.*, Science, 264, 1313, 1994]

- Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is the sixth mission of NASA Small Explorer missions (SMEX). Launched on February 5, 2002 from the vehicle Pegasus.

- RHESSI is designed to image solar flares in energetic photons from soft X-rays ($\sim$3 keV) to gamma-rays (up to $\sim$20 MeV).



Artist's conception of RHESSI orbiting above the triggering of a TGF. Credit: NASA.

- *Smith et al.* [Science, 307, 1085, 2005] reported the observation of TGFs up to 20 MeV by RHESSI.

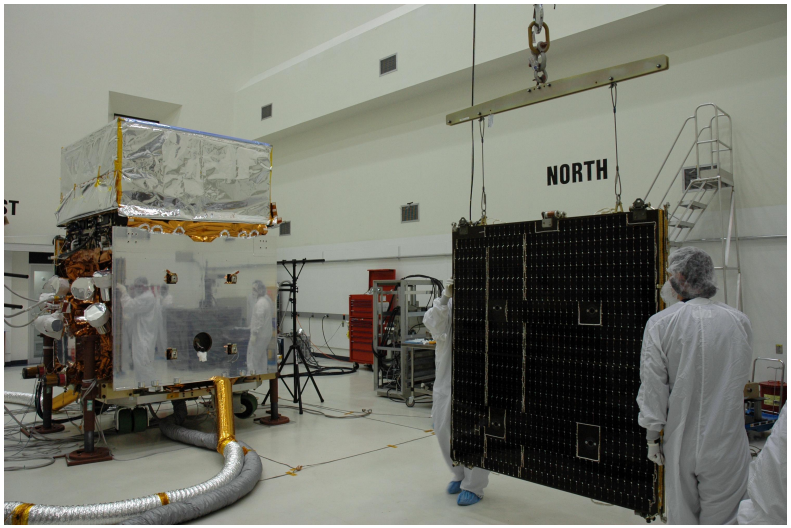
- The Astro-rivelatore Gamma a Immagini (AGILE) is an X-ray and gamma-ray astronomical satellite of the Italian Space Agency (ASI). It was launched successfully into orbit on April 23, 2007 by the Indian PSLV-C8 launch vehicle.

- *Marisaldi et al.* [JGR, 115, A00E13, 2010] reported the detection of TGF events by the MCAL instrument (CsI(Tl) minicalorimeter) aboard AGILE from 0.5 up to 40 MeV.

AGILE assembly. Credit: IASF/ASI.

- The Fermi Gamma-ray Space Telescope was launched on 11 June 2008 aboard a Delta II 7920-H rocket in order to perform gamma-ray astronomy observations.

- Fermi consists of 2 instruments: the Gamma-ray Burst Monitor (GBM) and the Large Area Telescope (LAT).



Technicians guide one of twin solar arrays toward the Gamma-ray Large Area Space Telescope. Credit: NASA.

- *Briggs et al.* [JGR, 115, A07323, 2010] reported detection of TGFs with typical energy $\sim$30 MeV, with one TGF having a 38 MeV photon.

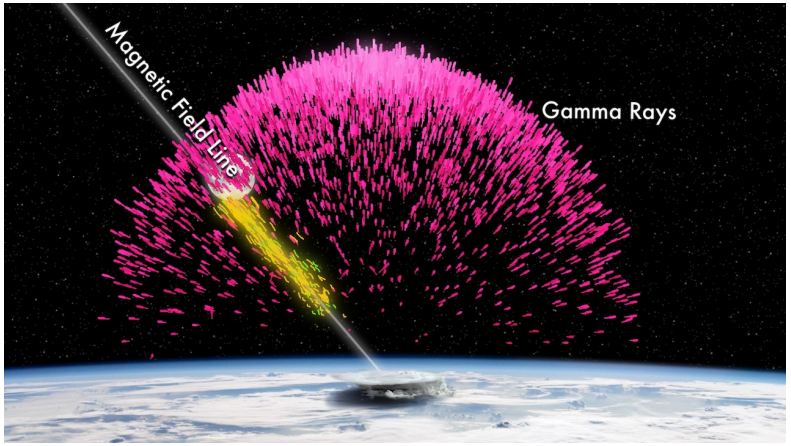
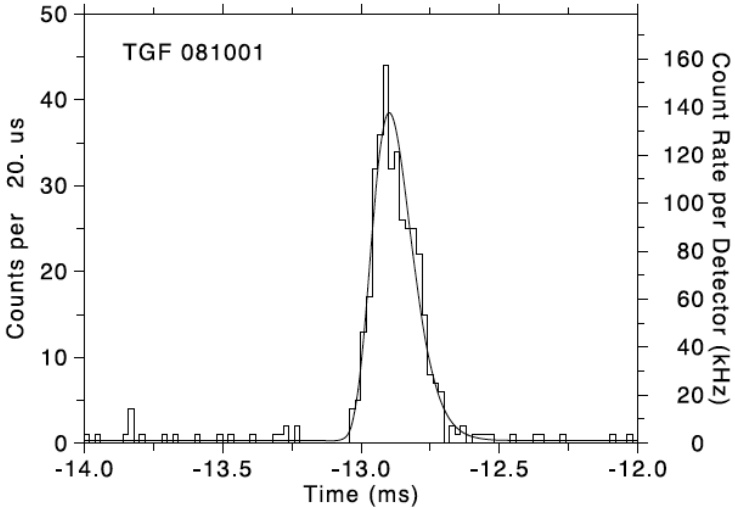
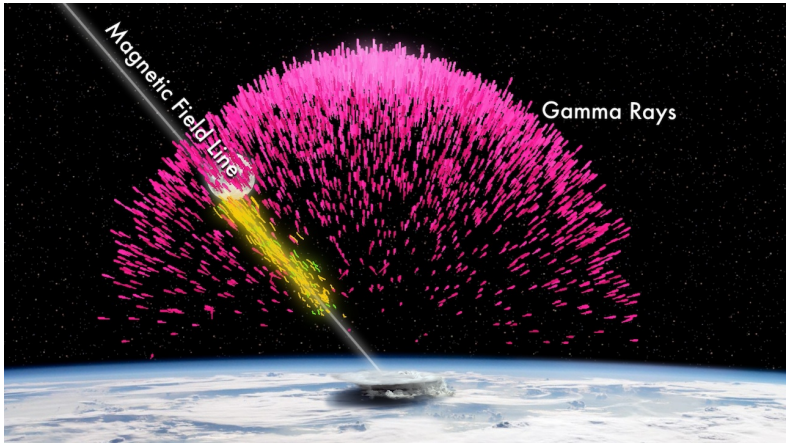


Illustration of a TGF. Credit: NASA/Goddard Space Flight Center / J. Dwyer, Florida Inst. of Technology



Example of a TGF detected by Fermi-GBM [*Briggs et al.,* JGR, 115, A07323, 2010].

- Typical max. energy: ∼30 MeV.
  - Max. energy reported (AGILE): 100 MeV (!)
- Typical duration: fraction of ms.
  - AGILE reports events lasting typically a few ms, other missions report events lasting ∼0.3 ms.
- Typical fluence: $\gtrsim$1 photon/cm^2 when observed from low-orbit.
  - The maximum TGF fluence is yet to be established (due to deadtime, pile-up, etc.).



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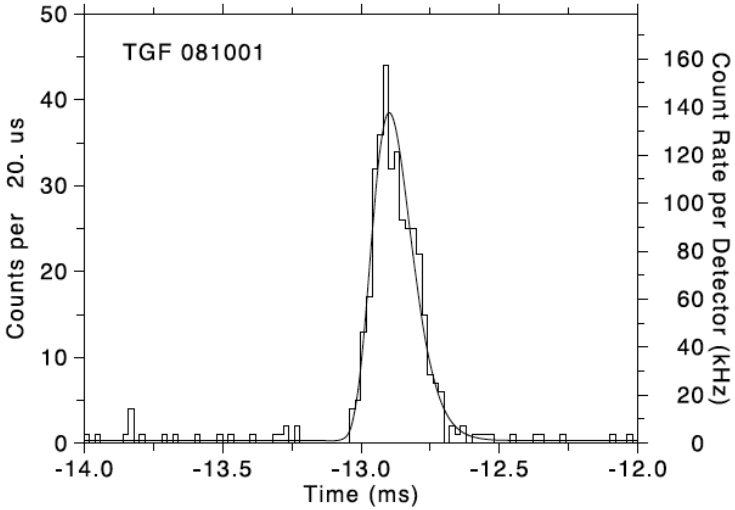

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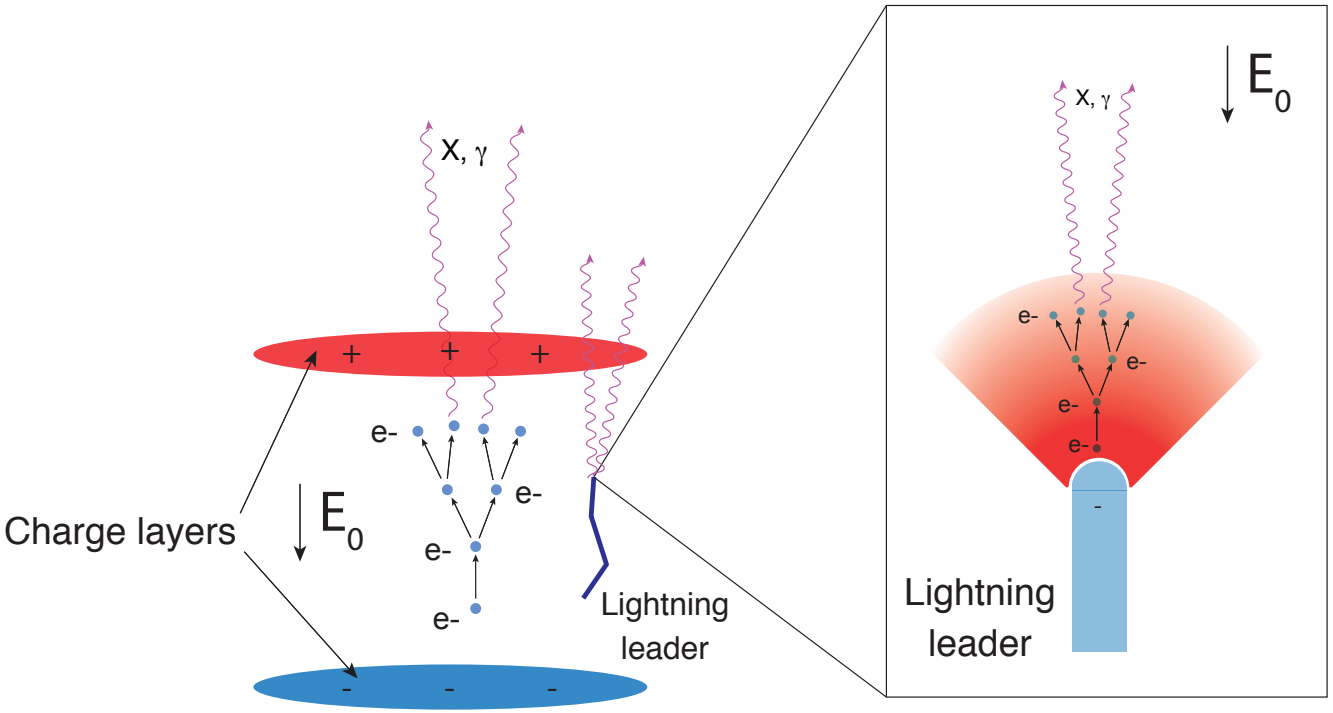
What is the origin of these energetic radiation bursts?

Two theories to explain TGFs



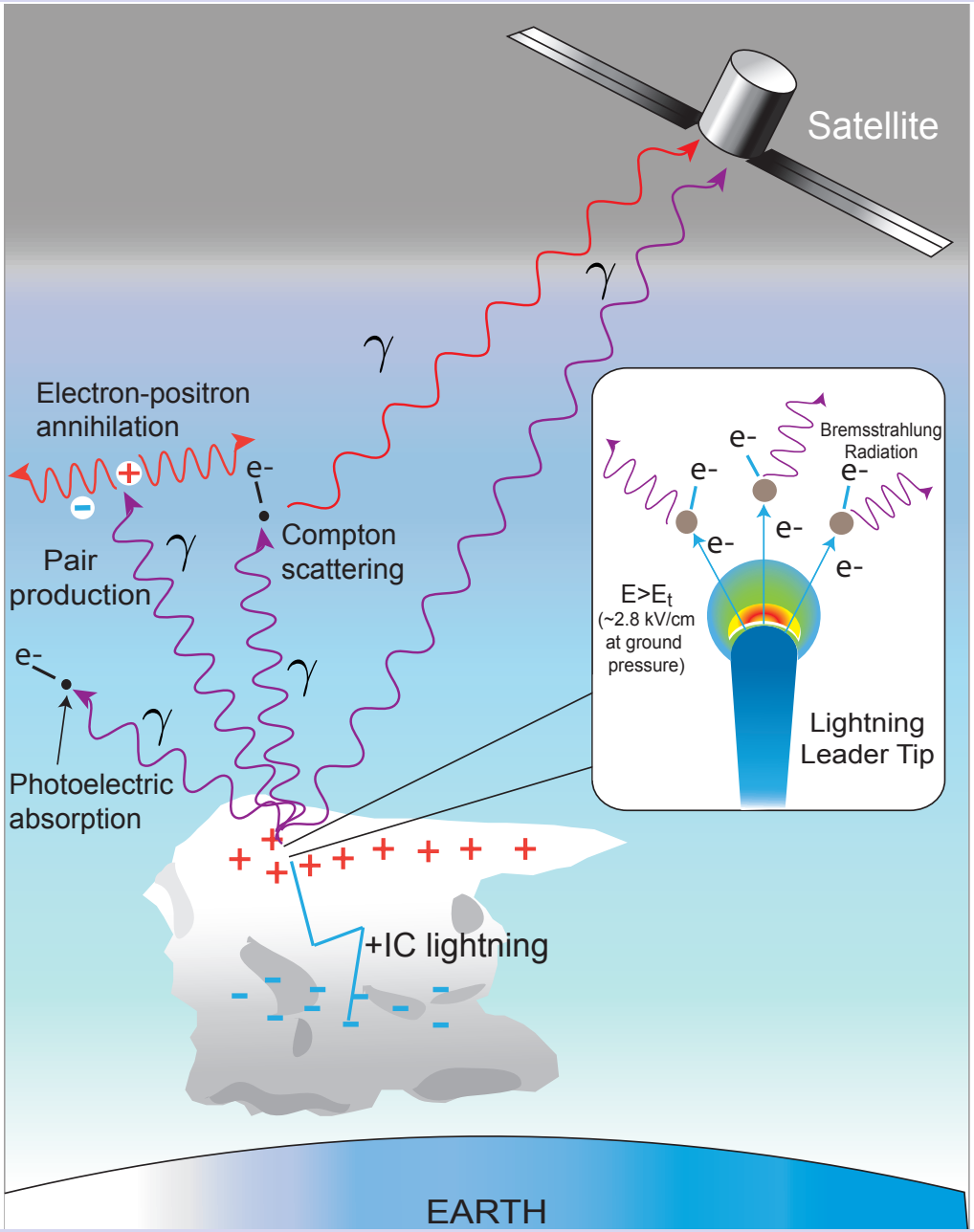
RREA in thunderstorm weak electric field [e.g., *Dwyer*, JGR, 113, D10103, 2008]

Thermal runaway electrons in the leader field [e.g., *Celestin and Pasko*, JGR, 116, A03315, 2011]

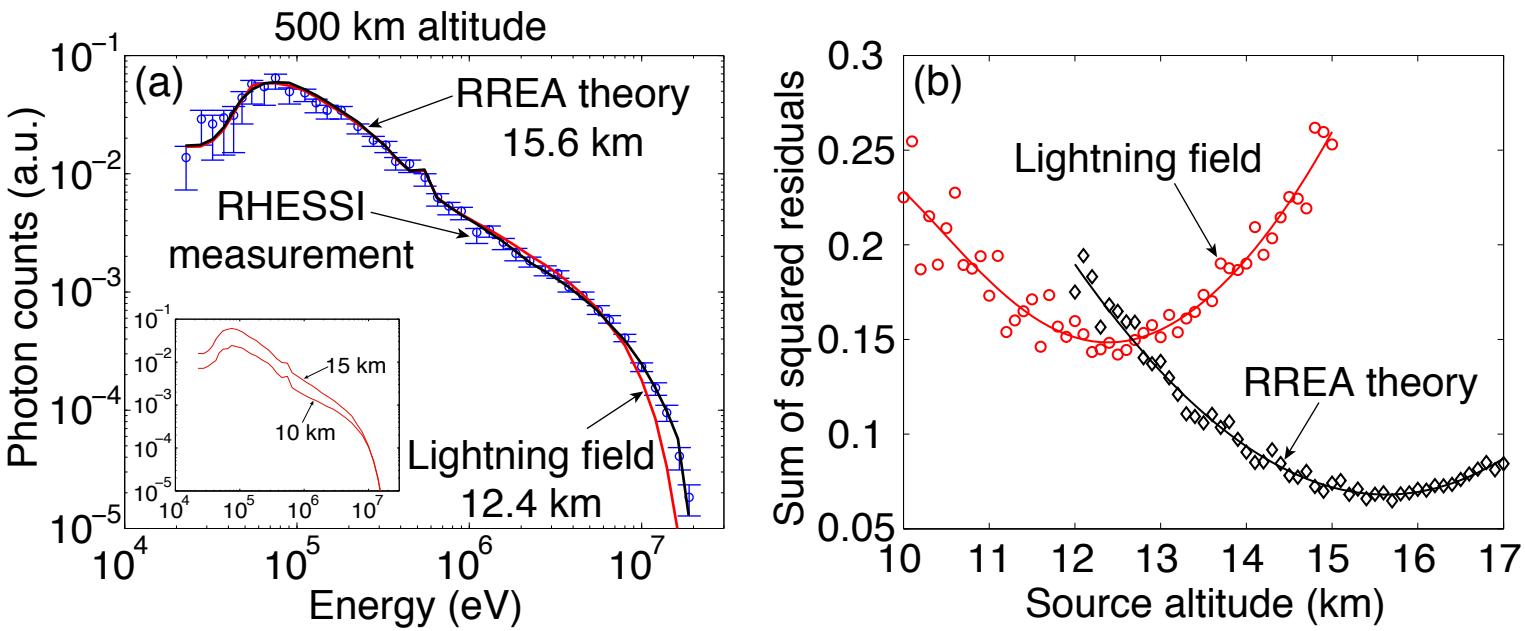
Link between lightning and TGFs

- *Stanley et al.* [GRL, 33, L06803, 2006] have established a direct link between positive intra-cloud (+IC) lightning (propagating between lower negative and upper positive thundercloud charges) and TGFs.
- *Shao et al.* [JGR, 115, A00E30, 2010] have documented nine TGF-related lightning events observed by the Los Alamos Sferic Array (LASA). All TGF-related events detected by LASA were exclusively related to +IC discharges transporting electrons upward, whereas the majority of LASA's data were composed of cloud-to-ground (CG) return strokes.
- Measurements have correlated TGFs with initial development stages of normal polarity intracloud lightning that transports negative charges upward (+IC) [*Lu et al.*, GRL, 37, L11806, 2010; JGR, 116, A03316, 2011].
- *Cummer et al.* [GRL, 38, L14810, 2011] have recently shown a close association between TGFs detected by the Fermi-GBM and fast lightning processes within several tens of microseconds.
- Altitude at the moment of the TGF production: 10.5–14.1 km [*Shao et al.,* JGR, 2010] and 8.5–13 km [*Lu et al.,* GRL, 2010].

Monte Carlo model to simulate photon transport



Source altitude determination and comparison to RHESSI measurements



RHESSI data are reproduced from [*Dwyer and Smith*, GRL, 32, L22804, 2005]. The detector response matrix was taken from `http://scipp.ucsc.edu/~dsmith/tgflib_public/data/`

[*Xu et al.*, GRL, 39, L08801, 2012, Figure 2]

Open questions

- What physical mechanism in thunderclouds actually produce TGFs? (RREA? lightning? Something else?)
- What are the effects of the acceleration of the large number of runaway electrons on the thundercloud electricity? (T-cloud electrification, impact on lightning propagation, etc.)
- Link with relativistic electron/positron beams [*Dwyer et al.*, GRL, 35, L02815, 2008; *Briggs et al.*, GRL, 38, L02808, 2011].
- What is the actual global frequency of TGFs?
- What are TGFs characteristics when excluding instrumental alteration? (fluence, spectra, duration, etc.).

Many open questions

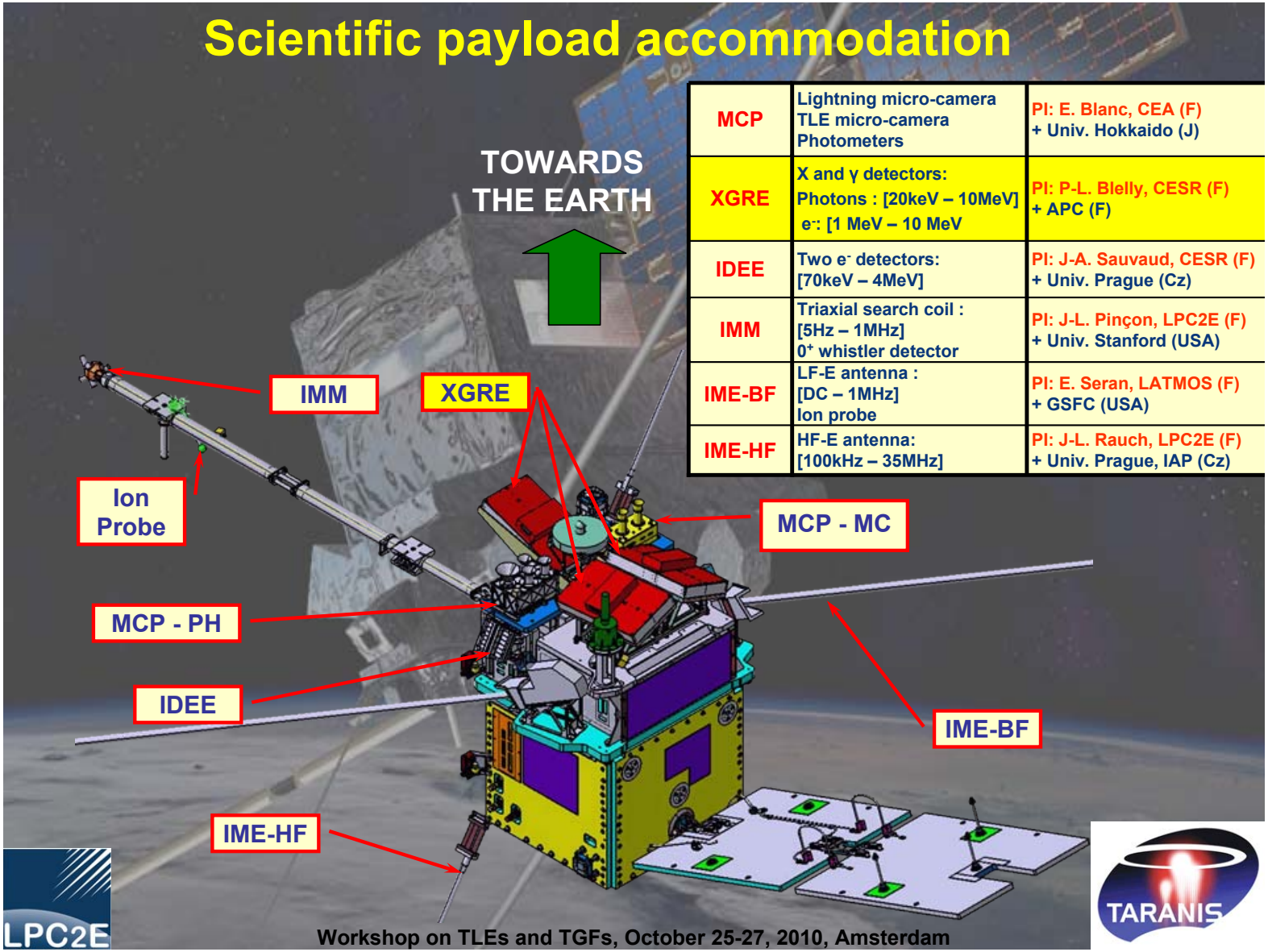
- Are there TGFs produced in other planetary atmospheres?
- What is the corresponding neutron yield? [e.g., Carlson et al., JGR, 115, A00E19, 2010].
- What is the actual danger related to radiation doses received by aircraft passengers and crew flying near thunderstorms [*Dwyer et al.*, JGR, 115, D09206, 2010] ?
- etc.

TARANIS satellite: observation of TLEs and TGFs

An illustration of the TARANIS satellite. Credit: CNES / D. Ducros.

TARANIS (Scientific payload PI (J.-L. Pincon, LPC2E); Technical payload PI (D. Lagoutte, LPC2E)).

TARANIS instruments

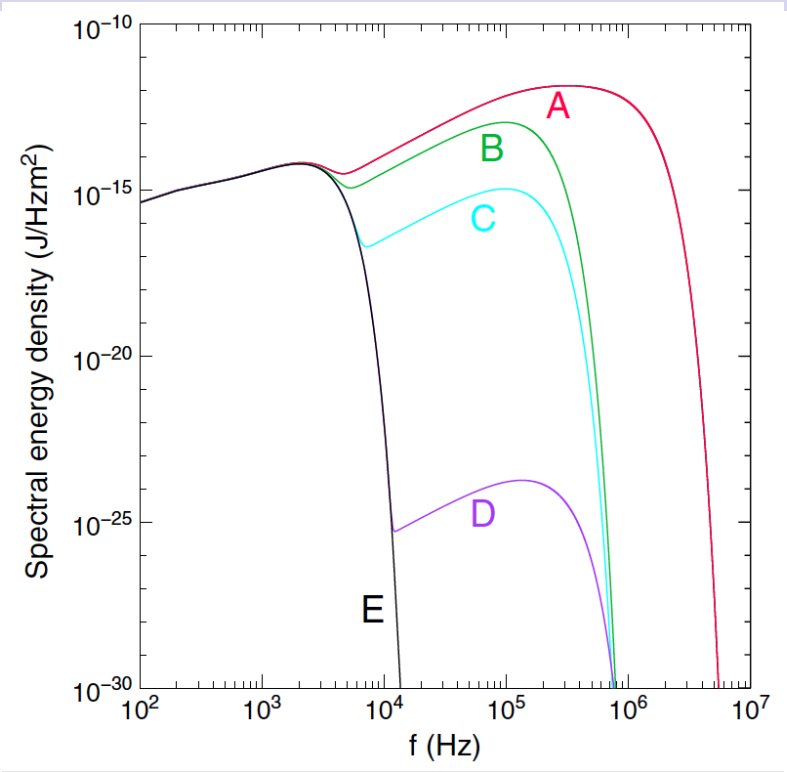


MCP	Lightning micro-camera TLE micro-camera Photometers	PI: E. Blanc, CEA (F) + Univ. Hokkaido (J)
XGRE	X and γ detectors: Photons : [20keV – 10MeV] e^-: [1 MeV – 10 MeV	PI: P-L. Blelly, CESR (F) + APC (F)
IDEE	Two e^- detectors: [70keV – 4MeV]	PI: J-A. Sauvaud, CESR (F) + Univ. Prague (Cz)
IMM	Triaxial search coil : [5Hz – 1MHz] 0^+ whistler detector	PI: J-L. Pinçon, LPC2E (F) + Univ. Stanford (USA)
IME-BF	LF-E antenna : [DC – 1MHz] Ion probe	PI: E. Seran, LATMOS (F) + GSFC (USA)
IME-HF	HF-E antenna: [100kHz – 35MHz]	PI: J-L. Rauch, LPC2E (F) + Univ. Prague, IAP (Cz)

HF (>3 MHz) emissions from TGFs?

- Open question. No direct relation observed yet. VHF emissions usually associated with leader stepping processes.
- Very fast processes ($\sim$30 ns) may be present in very high-energy TGFs [Celestin et al., JGR, 117, A05315, 2012].
- Estimates hint that HF emissions, if they exist, would be observed at close range [Dwyer et al., JGR, 114, D09208, 2009; Dwyer and Cummer, JGR, 118, 3769, 2013].
- Observation of this emission could validate or invalidate working theories [Dwyer and Cummer, JGR, 118, 3769, 2013].

Long range predicted power spectrum



Spectral energy density per unit area (J/Hz m^2) for the electromagnetic radiation from the TGF at a radial distance of 500 km for the four source models described in Table 2. Taken from [Dwyer and Cummer, JGR, 118, 3769, 2013, Figure 4].

Table 2. TGF Model Parameters

Model	Name of Model	N_p	σ_s (μ s)	κ (m)
A	Fast lightning source (Celestin, Xu, and Pasko)	30	0.03	50
B	Slow lightning source 1	100	1	220
C	Slow lightning source 2	10000	1	220
D	Relativistic feedback discharge	10^{13}	0	220
E	Infinite number of avalanche pulses	∞	0	220

Conclusions

- Terrestrial Gamma-ray Flashes (TGFs) are intense high energy photon bursts produced in the Earth's atmosphere in correlation with thunderstorms and observed from space.
- Many open questions.
- HF/VHF emissions may reveal new processes in the production of TGFs.
- Synergies between NenuFAR and TARANIS may be found and should be looked for.

Thank you for your attention.