Over in a Flash: A decade of Terrestrial Gamma-ray Flashes with Fermi-GBM

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10 years of TGFs with GBM

- Snapshot of TGFs – What are they?
- How has our picture developed since GBM?
- What does the future hold?
Terrestrial Gamma-ray Flash (TGF) “Cheat Sheet”

- Serendipitously discovered by BATSE on CGRO in 1991.
- Sub-ms pulses (Typically ~ 200 µs).
- Energy spectrum extends over tens of MeV.
- Continuum spectrum, sometimes with a 511 keV annihilation (e-p) line (ground).
- Initially believed to occur withSprites at an altitude of ~ 90 km until 2005, later found to occur < 20 km.
- Widely believed to be produced during +IC lightning as bremßtrahlung from the acceleration of high-energy seed electrons in the electric fields of thunderstorms.
Proposed Bremßtrahlung Initiation Mechanisms

- Relativistic Runaway Electron Avalanche (RREA)
- Relativistic Feedback Discharge (RFD)
- Lightning Leader Model

Sci. Amer. 292, 64, 2005
• **Relativistic Runaway Electron Avalanche (RREA)**

  Cosmic-ray seed particle or radio-active isotope decay.

• **Relativistic Feedback Discharge (RFD)**

  Adds Feedback: Positrons and back-scattered photons from avalanche propagate back to the source region.

• Additional seeds - more avalanches.

*Sci. Amer. 292, 64, 2005*


Proposed Bremßstrahlung Initiation Mechanisms

- **Lightning Leader Model**
  - Lightning leader can also produce a distribution of seed particles.
  - Space leader fuses to -ve leader, electric potential transferred to space leader in an ionising wave.
  - Ionisation channels of streamers limit the lateral expansion of the wave, enhancing the peak electric field.

*Dwyer 2008, JGR 113, D10103*

*Celestin & Pasko 2011, JGR 116, A03315*

*Babich et al., JGR, 120, 6, 5087-5100, 2015*
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Fermi Gamma-ray Space Telescope

Launched in 2008

Orbit: 565 km (LEO)
Inclination: 25.6 deg.

Large Area Telescope (LAT)

- Pair Production Telescope
- 20 MeV - 300 GeV.

Gamma-ray Burst Monitor (GBM)

- 12x NaI: 12.7 x 1.27 cm.
- 2x BGO: 12.7 x 12.7 cm.
- Energy Range: 8 keV - 40 MeV.

Image: NASA
The GBM

- Triggers in-orbit down to 16 ms for TGFs.
- These 16 ms algorithms include:
  - Two Nals, > 300 keV
  - Two Nals, > 100 keV
  - Two Nals and one BGO
  - Two BGOs
- Also found offline in TTE data (2 µs resolution) and screened by advocates and the LAT for glitches, cosmic rays, etc.
How has GBM helped our understanding of TGFs?

Major Contributions to the field include:

- **2010**: Connaughton et al. JGR 115, A12
  1/3 VLF association rate, ~40 µs TGF-VLF radio offset.

- **2011**: Briggs et al. GRL, 38, L02808
  Discovery of positrons in Electron Beams with GBM.

- **2013**: Briggs et al. JGR, 118, 6
  Rates, TTE, 1st unofficial catalog.
  Connaughton et al. JGR 118, 2313-2320
  TGFs emit radio, 200 µs simu, VLF match rate.

- **2014**: Fitzpatrick et al. PRD 90(4), 043008
  MC simulations of RREA, rules out basic RREA.
  Foley et al. JGR 119, 7, 5931-5942
  Pulse properties – asymmetry, electron flux estimates.

- **2016**: Chronis et al. BAMS, D-14, 00239
  Meteorological paper - any storm can create a TGF.

- **2017**: Roberts et al. JGR, 2017JA024837
  Tropical Storm TGFs.

- **2018**: Mailyan et al. JGR 123, 7, 2018JA025450
  TGFs with NLDN. 4/5 TGFs peak current < 50 kA.
  Stanbro et al. JGR, 10.1029/2018JA025710
  Multi-pulsed TGFs (consecutive). Recharge time.

... And many many more through extensive collaboration!
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The First Fermi-GBM Terrestrial Gamma Ray Flash Catalog

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Key Points:
- This catalog contains the largest released samples of TGFs and associated radio data.
- This study shows quantitatively that TGFs preferentially occur over land near coastlines.
- A Bayesian block algorithm was used to extract the spectral and temporal properties of each TGF.

- 4144 TGFs from 8 years of GBM data (>5000 now).
- ~1/3 of these (>1600 now) have associated WWLLN sferic.
- TGF Rate steadily increasing, due to detection method upgrades.
- Primary purpose of paper is to describe public data on FSSC and analyse largest sample of TGFs.
Correlations with VLF

- Without a VLF correlation, source location of GBM TGF limited to 800 km area centered on the nadir.
- VLF correlation using ENTLN or WWLLN gives true source location to within 20 km.
- Uneven detection efficiencies between the ENTLN and WWLLN.
- WWLLN biased to short duration TGFs (Connaughton, 2013).
- Can use correlations to probe the storms that produce TGFs in great detail.
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>4000 TGFs (All)

>1300 TGFs (VLF)
**Figure 12.** Top: Three years of TGF data from the months of December, January and February (DJF). Bottom: Two years of TGF data from the months of June, July and August (JJA). Both Plots: Blue markers are TGFs without a VLF association, yellow markers denote TGFs with a VLF association. The SAA region (grey shaded region) and inclination of *Fermi* are also shown. On average, about 30 to 50 TGFs are detected by GBM during December, January and February (DJF) and 70 to 100 during the northern hemisphere summer months of June, July and August (JJA).
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Temporal/Geographical Variation
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Temporal/Geographical Variation

TGF source locations < 200 km of coastline.

As above, but each bin normalized to time Fermi spends at offset from coastline and over sea/land. Accumulated using Fermi’s 2015 orbit.
TGF source locations < 200 km of coastline.

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Bayesian Block Analysis

- Hardness Ratio = 316 keV.
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- WWLLN times of group arrival minus the center times of the TGF discovery bins after accounting for light travel time.

- Difference between peak discovery bin time and BB peak time. – Good agreement.

- Delay between soft ( <300 keV) and hard (>300 keV) photons per TGF. **Mean delay of 27 μs.**
  - Grefenstette, 2008: 28+/- 3 μs.
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The Future is Bright!
TGF Ground Studies:

- Focus shifting toward neutron detection and more into the photonouclear reactions in the atmosphere.

- More TGFs are being observed from the ground at altitudes below 2 km.

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The Future is Bright!
TGF Space-based Studies:

ASIM:

- The ASIM MXGS instrument carries two sets of detectors for TGFs: 15 keV to 400 keV and 200 keV to 40 MeV. The low energy detector has 128x128 channels with a high mass density coded mask - Direction to the TGF source.

- Correlation with other instruments (optical imaging by the MMIA instrument, lightning and TLEs).

GLM (GOES-16):

Geostationary Lightning Mapper is a single-channel, near-infrared optical transient detector that can detect the momentary changes in an optical scene, indicating the presence of lightning. GLM measures total lightning (in-cloud, cloud-to-cloud and cloud-to-ground) activity continuously over the Americas and adjacent ocean regions with near-uniform spatial resolution of approximately 10 km.

- Staring CCD imager (1372x1300 pixels)
- Near uniform spatial resolution 8 km nadir, 14 km edge fov
- Coverage up to 52 deg N lat
- 0-90% flash detection day and night
What’s next for GBM?

- GBM has the largest collection of TGFs detected (+5000).

- Of these 5000+ TGFs, through extensive collaboration with world-wide lightning networks, GBM has helped create the largest database of TGFs emanating from storms to an accuracy of 10-20 km – The size of a storm.

- Only joint TGF+TEB detection.

- Due to the large sample of TGFs GBM has collected (and continues to collect), the instrument is a valuable player in the field, where many groups use the free public data.
What next for GBM?

• Looking forward. GBM’s involvement in TGF science continues to be strong and evolve with the fast pace of the field.

• With the launch of GLM, GBM will undoubtedly help in determining when the TGF occurs during the lightning process with higher certainty – correlations with optical flash (GLM) and radio sferic (WWLLN) - Complete EM picture.

This will help narrow existing initiation mechanism models!

• Future projects involving multiple radiation detection to look in–detail at the photo-nuclear reactions that occur in the sky.
Happy Birthday Fermi!

Scientists study terrestrial gamma-ray flashes produced by tropical storms

As tropical systems grow in size and strength, their clouds are pushed higher into the atmosphere where intense electrical fields can develop, yielding terrestrial gamma-ray flashes.

April 24 (UT) — For the first time, researchers have analyzed terrestrial gamma-ray flashes produced by tropical storms. Terrestrial gamma-ray flashes, or TGFs, are one of the most intense forms of light naturally produced on Earth. Since 2008, NASA’s Fermi Gamma-ray Space Telescope has recorded more than 4,000 TGFs, each of which last less than an millennium and produce several million times the energy of natural light. Until now, scientists had studied flashes produced by tropical storms, hurricanes or supernovas.
Relativistic Runaway Electron Avalanches (RREAs)
Gurevich et al. (1992)

The avalanche length, $\lambda$, is the e-folding length.

From Dwyer et al. (2012)
Relativistic feedback discharge (RFD) aka “Dark Lightning” due to x-rays and positrons.

The central avalanche is due to the injection of a single, 1 MeV seed electron. All the other avalanches are produced by x-ray and positron feedback. The top panel is for times, $t < 0.5$ μs. The middle panel is for $t < 2$ μs, and the bottom panel is for $t < 10$ μs.

From Dwyer (2007)
Simulation results showing a RFD inside a thundercloud, including Earth’s magnetic field

From Dwyer.
• 37 TGFs found using WWLLN and ENTLN VLF associations.

• TGFs come predominately from strengthening phase of storm.

• Oceanic lightning may be prolific TGF producer.

TGF is ~600 km from land & ~800 km from storm-center.

16, 88 sferics within 100 km and 1000 km, all within +/- 600 s.

4 pulses over 4 ms. First pulse had a sferic association, unlike observations by Mezentsev et al., 2016.
ENTLN Detection Efficiency

2014, Time window = 10 micro sec, Space window < 30km

V. Bui et al., IEEE 2015 CSCI, 386–391, (2015), doi:10.1109/CSCI.2015.120.
Terrestrial Electron Beams (TEBs)

1. They are typically longer than TGFs (>1 ms) due to the dispersion as they propagate through the atmosphere.
2. They exhibit a strong 511 keV spectral line, due to electron-positron annihilation.
3. A strong asymmetry between the signals in the BGO detectors, due to the softer spectra of TEBs.
4. A mirror pulse visible in the lightcurve due to magnetic mirroring at the conjugate point of the Earth’s magnetic field line.
5. A lack of lightning activity at the spacecraft nadir, while showing lightning activity at the magnetic footprints.

Fermi GBM positron event
The Transient sky