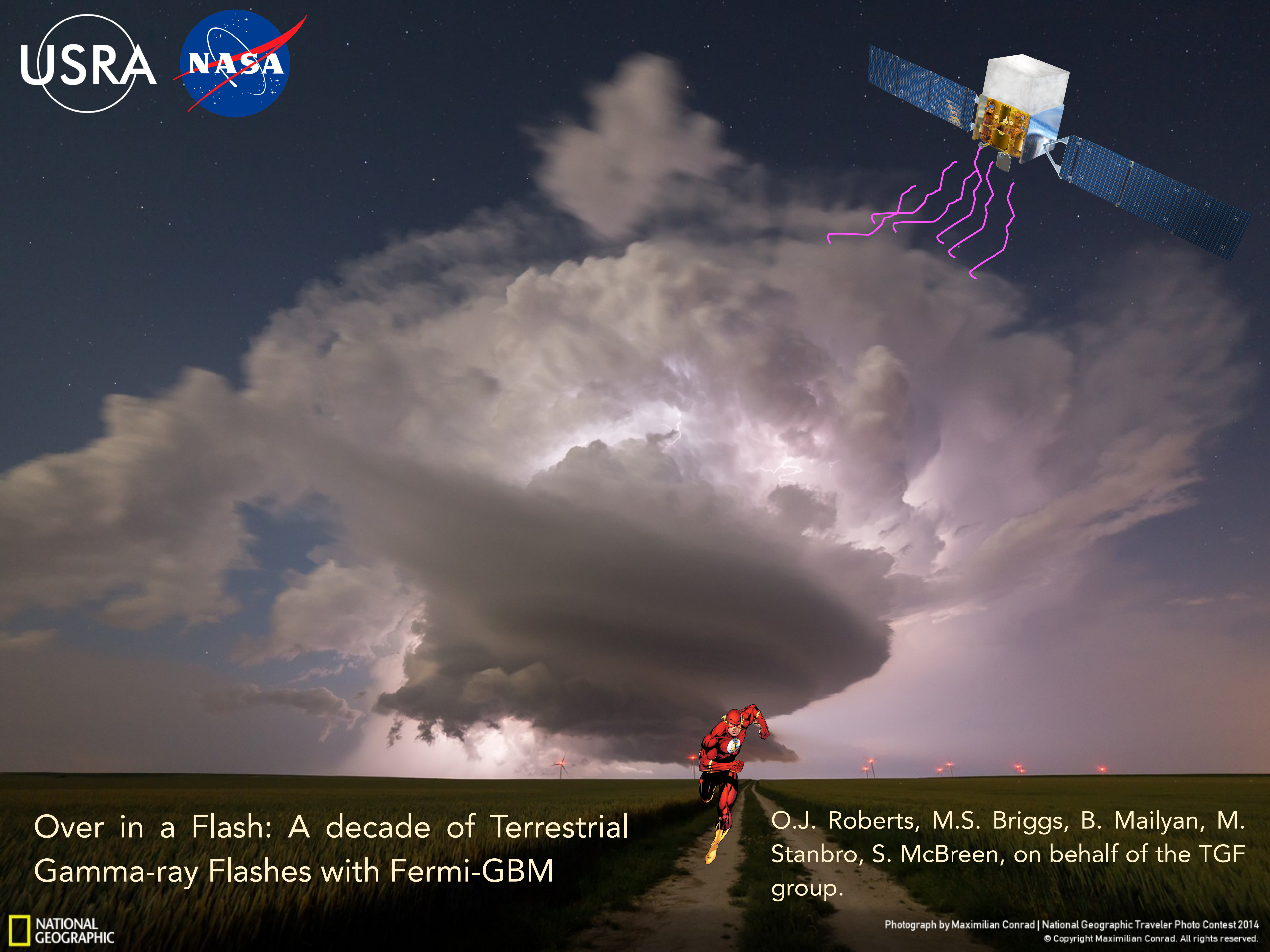


Over in a Flash: A decade of Terrestrial Gamma-ray Flashes with Fermi-GBM

O.J. Roberts, M.S. Briggs, B. Mailyan, M. Stanbro, S. McBreen, on behalf of the TGF group.

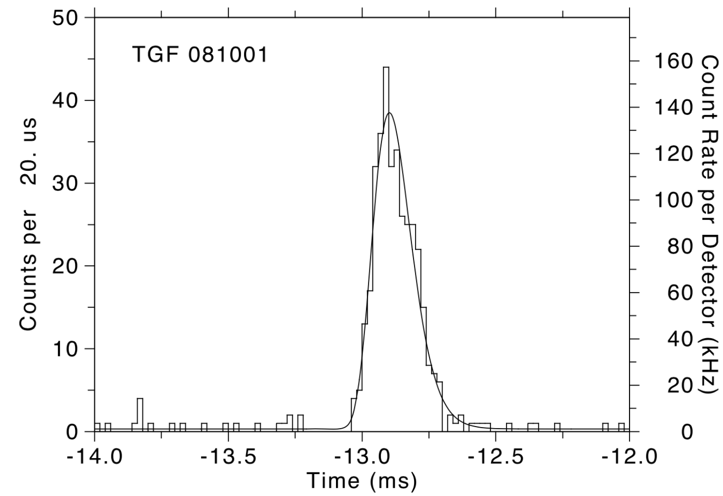
GBM-TGF Group

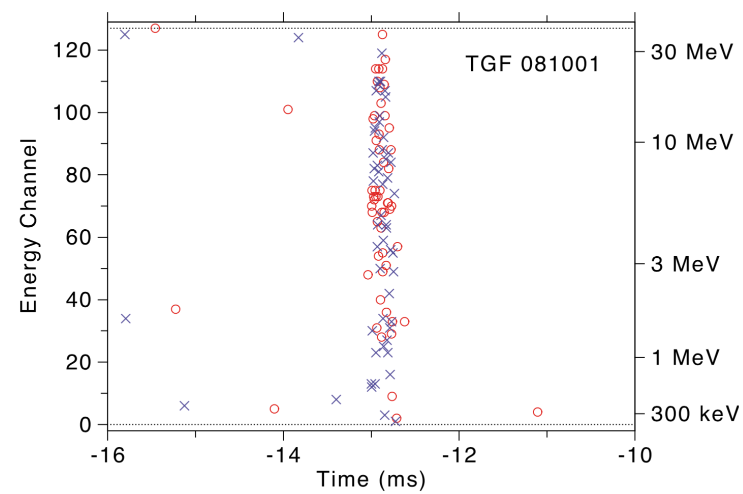
10 years of TGFs with GBM

- 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 with Sprites 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.

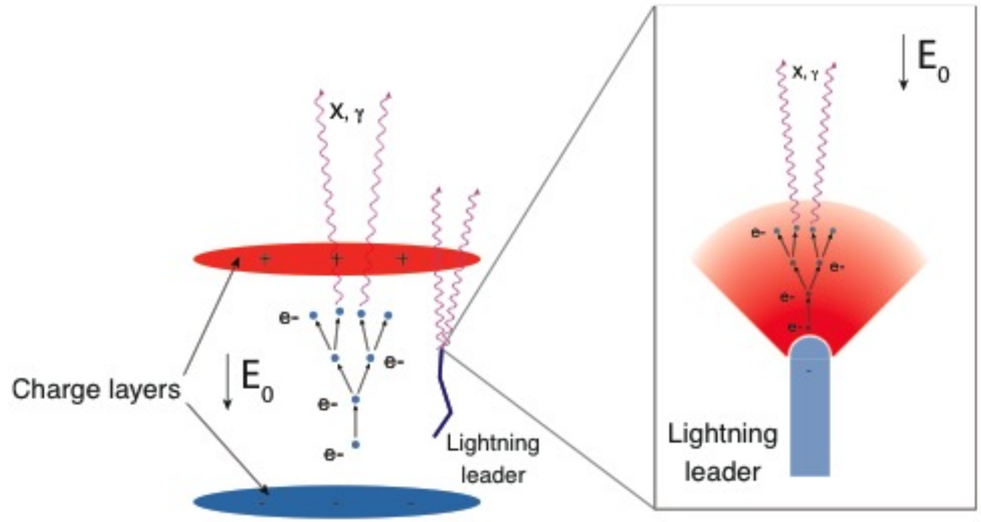


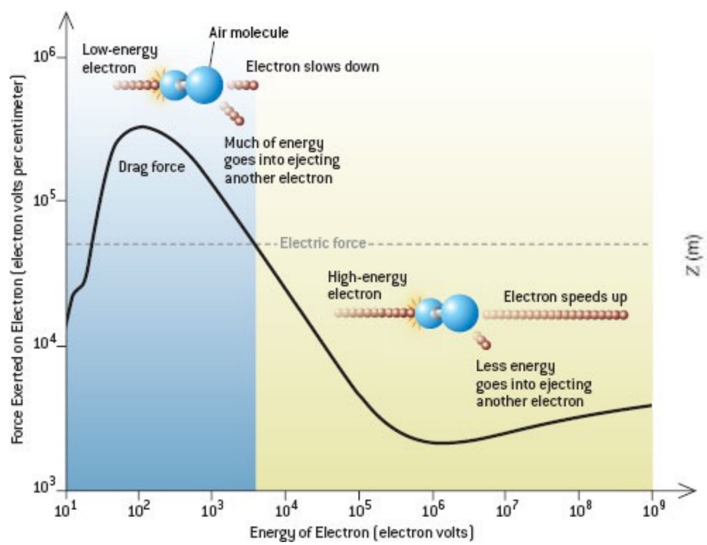


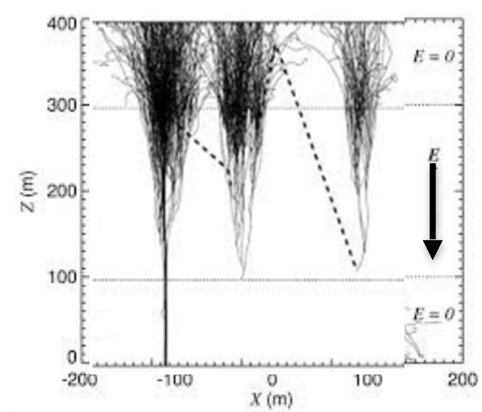
Briggs et al. 2010, JGR 115, A073232

Proposed Bremßtrahlung Initiation Mechanisms

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







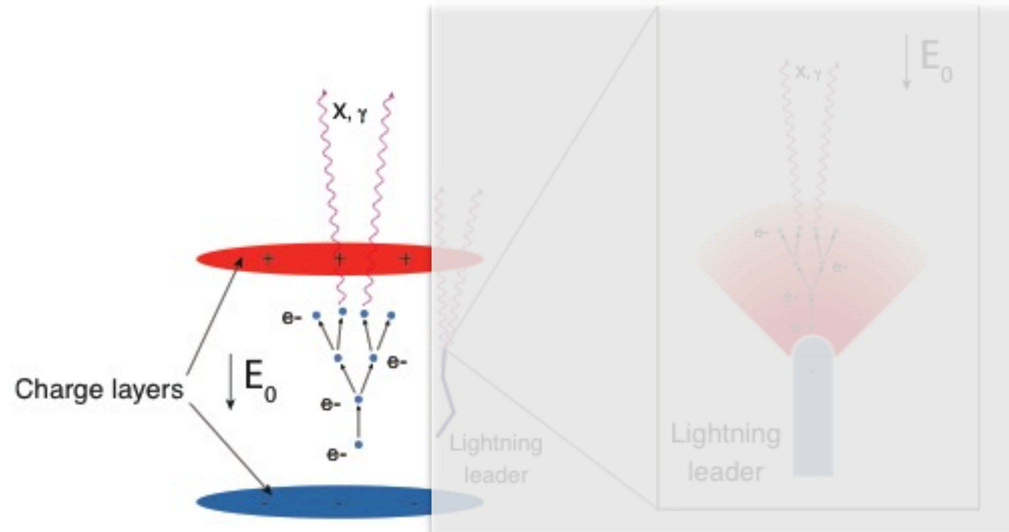
Sci. Amer. 292, 64, 2005

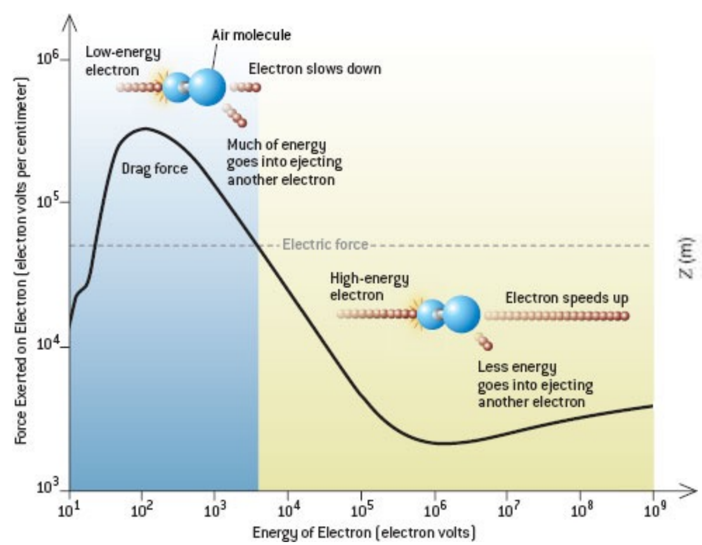
Gurevich, Phys. Letts. A., 165, 463, 1992.

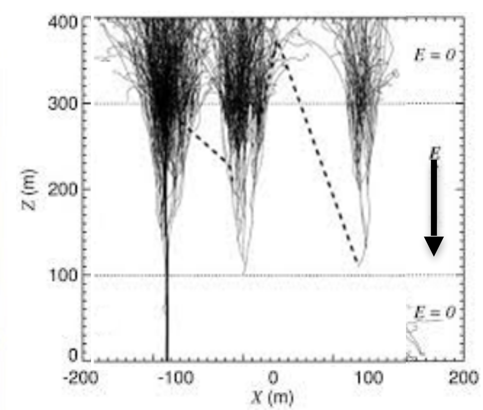
Dwyer, Geo. Phys. Res., 30, 20, 2055, 2003.

Proposed Bremßtrahlung Initiation Mechanisms

- **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

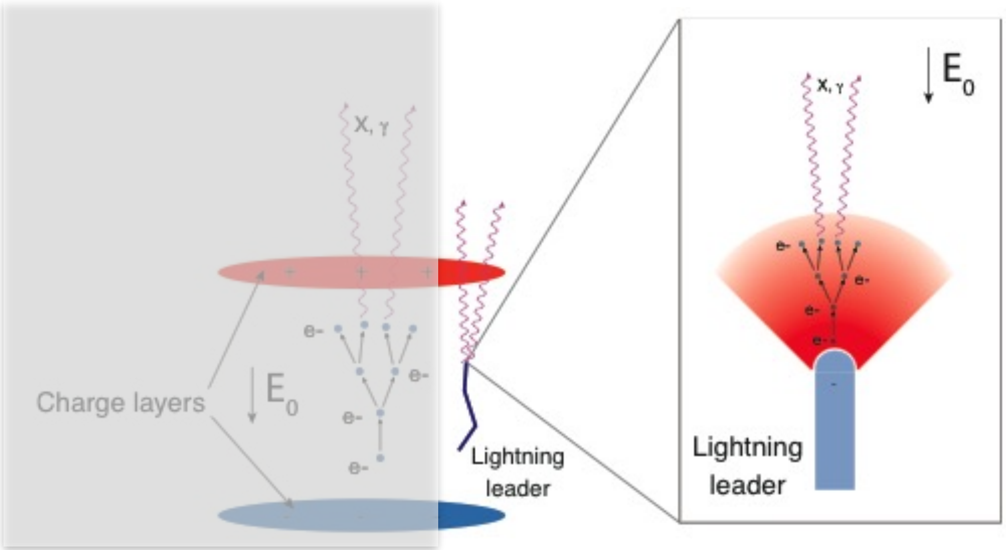
Gurevich, Phys. Letts. A., 165, 463, 1992.

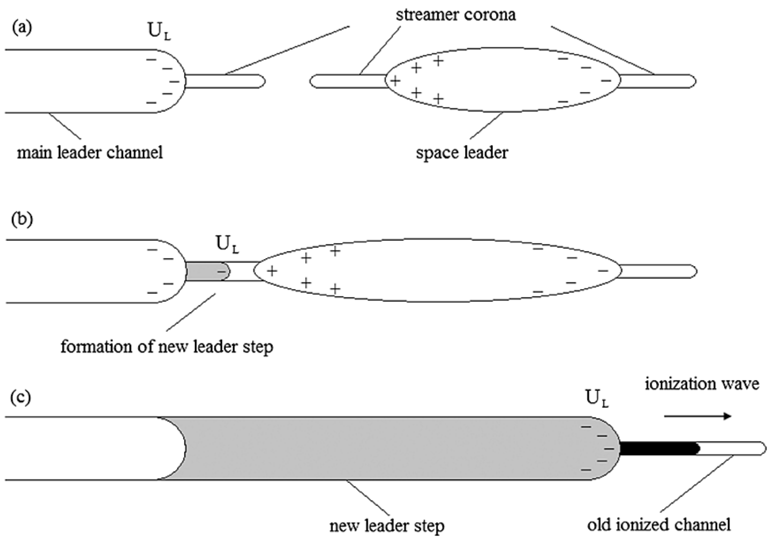
Dwyer, Geo. Phys. Res., 30, 20, 2055, 2003.

Proposed Bremßtrahlung 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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Image: NASA

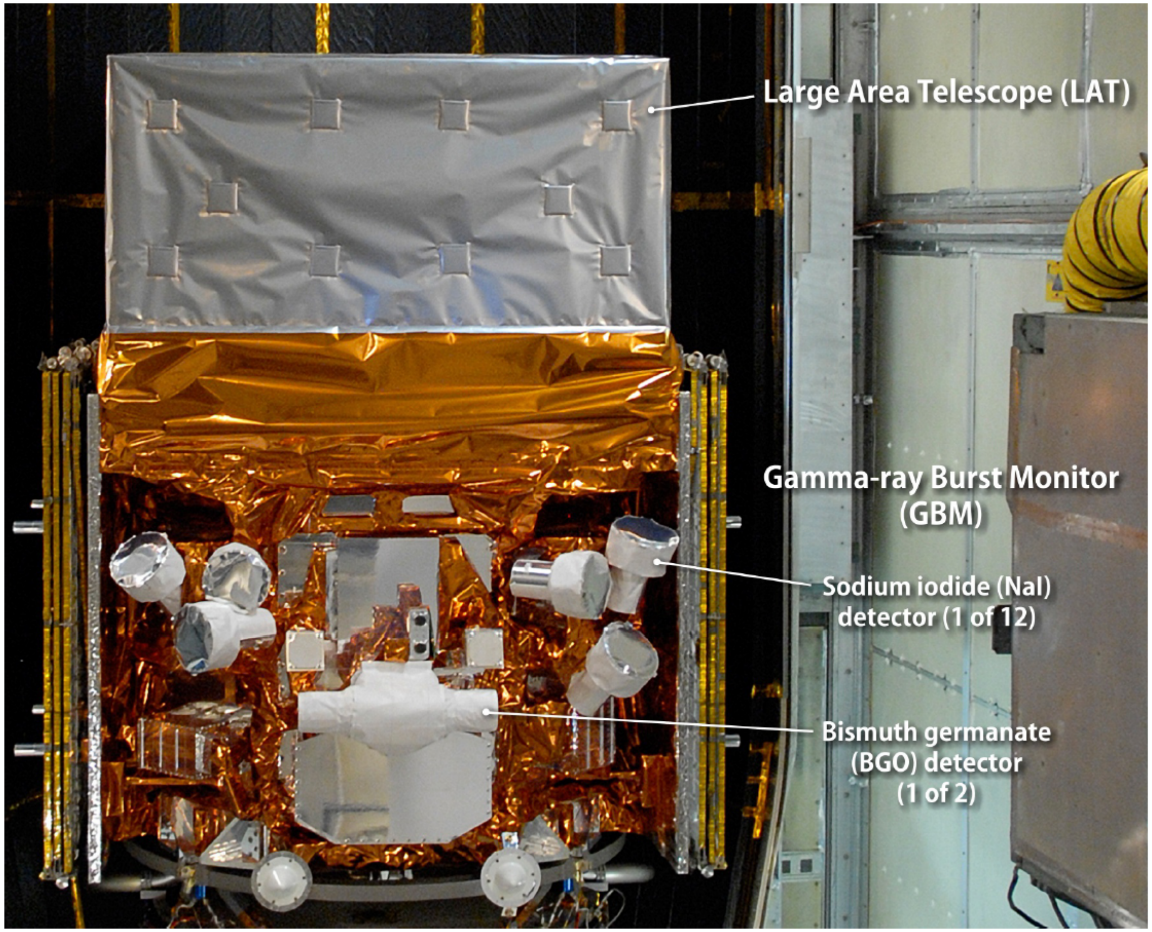
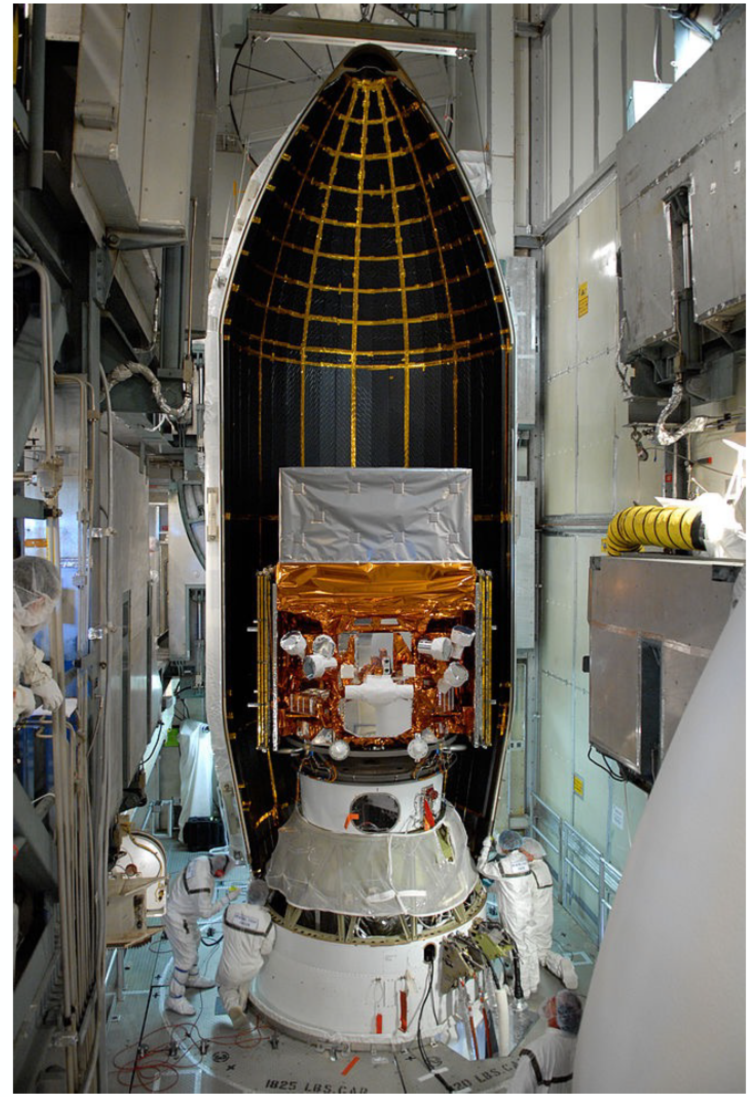


Image: NASA



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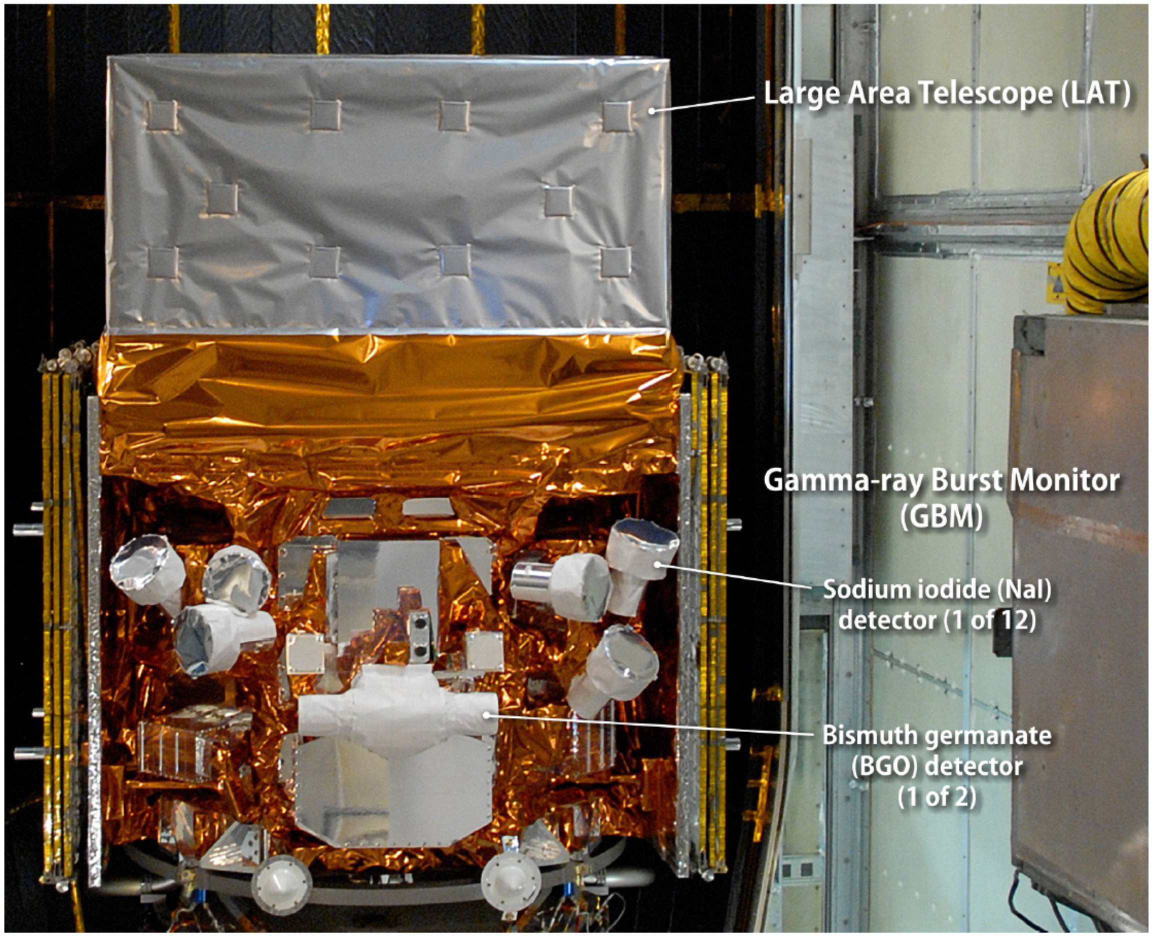

Image: NASA

Image: NASA

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

The GBM

- Triggers in-orbit down to 16 ms for TGFs.
- These 16 ms algorithms include:
  - Two NaIs, > 300 keV
  - Two NaIs, > 100 keV
  - Two NaIs 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),043,008
  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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Electron-positron beams from terrestrial lightning observed with Fermi GBM

Michael S. Briggs, Valerie Connaughton, Colleen Wilson-Hodge, Robert D. Preece, Gerald J. Fishman, R. Marc Kippen, P. N. Bhat, William S. Paciesas, Vandiver L. Chaplin, … See all authors

CHARACTERISTICS OF THUNDERSTORMS THAT PRODUCE TERRESTRIAL GAMMA RAY FLASHES

BY THEMISTOKLIS CHRONIS, MICHAEL S. BRIGGS, GEORGE PRIFTIS, VALERIE CONNAUGHTON, JAMES BRUNDELL, ROBERT HOLZWORTH, STAN HECKMAN, SHELIA MCBREEN, GERARD FITZPATRICK, AND MATTHEW STANBRO

Compton scattering in terrestrial gamma-ray flashes detected with the Fermi gamma-ray burst monitor

Gerard Fitzpatrick, Eric Cramer, Sheila McBreen, Michael S. Briggs, Suzanne Foley, David Tierney, Vandiver L. Chaplin, Valerie Connaughton, Matthew Stanbro, Shaolin Xiong, Joseph Dwyer, Gerald J. Fishman, Oliver J. Roberts, and Andreas von Kienlin
Phys. Rev. D **90**, 043008 – Published 20 August 2014

Radio signals from electron beams in terrestrial gamma ray flashes

Valerie Connaughton,[1,2] Michael S. Briggs,[1,2] Shaolin Xiong,[1] Joseph R. Dwyer,[3] Michael L. Hutchins,[4] J. Eric Grove,[5] Alexandre Chekhtman,[6] Dave Tierney,[7] Gerard Fitzpatrick,[7] Suzanne Foley,[7] Shelia McBreen,[7] P. N. Bhat,[1] Vandiver L. Chaplin,[1] Eric Cramer,[3] Gerald J. Fishman,[8] Robert H. Holzworth,[4] Melissa Gibby,[8] Andreas von Kienlin,[9] Charles A. Meegan,[10] William S. Paciesas,[10] Robert D. Preece,[1,2] and Colleen Wilson-Hodge[11]

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Terrestrial gamma-ray flashes in the Fermi era: Improved observations and analysis methods

Michael S. Briggs, Shaolin Xiong, Valerie Connaughton, Dave Tierney, Gerard Fitzpatrick, Suzanne Foley, J. Eric Grove, Alexandre Chekhtman, Melissa Gibby, … See all authors

Terrestrial gamma ray flashes due to particle acceleration in tropical storm systems

O. J. Roberts[1], G. Fitzpatrick[1,2], G. Priftis[3], K. Bedka[4], T. Chronis[3], S. McBreen[1], M. S. Briggs[2], E. Cramer[2], B. Mailyan[2], and M. Stanbro[2]

GBM-TGF Group

RESEARCH ARTICLE

10.1029/2017JA024837

The First *Fermi*-GBM Terrestrial Gamma Ray Flash Catalog

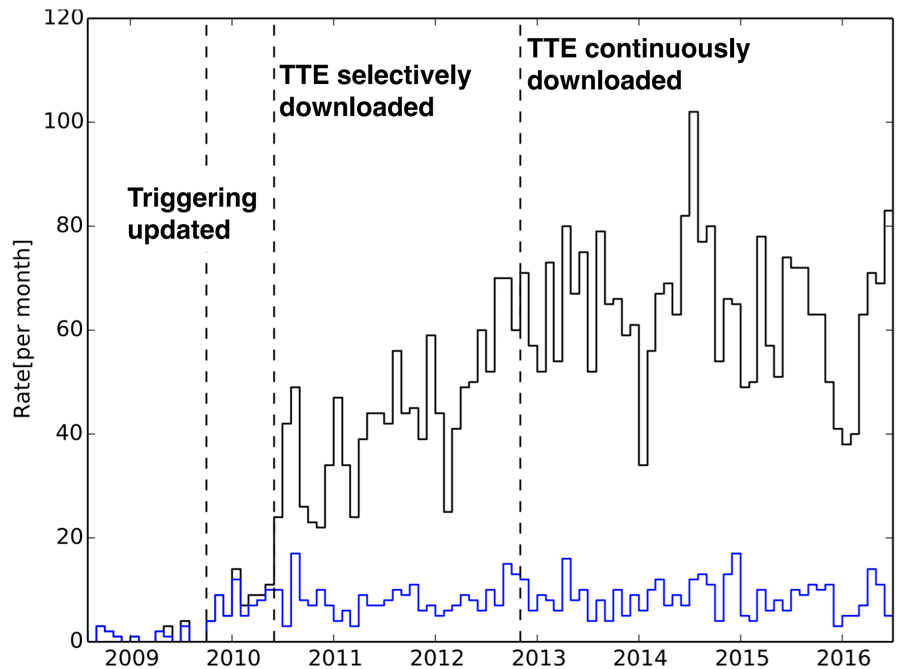
O. J. Roberts[1,2], G. Fitzpatrick[1,3], M. Stanbro[4], S. McBreen[1], M. S. Briggs[3,4], R. H. Holzworth[5], J. E. Grove[6], A. Chekhtman[7], E. S. Cramer[3], and B. G. Mailyan[3,8]

[1]School of Physics, University College Dublin, Dublin 4, Ireland, [2]Marshall Space Flight Center, National Space Science and Technology Center, Universities Space Research Association, Huntsville, AL, USA, [3]Center for Space Plasma and Aeronomic Research, University of Alabama in Huntsville, AL, USA, [4]Department of Space Science, University of Alabama in Huntsville, Huntsville, USA, [5]Earth and Space Sciences, University of Washington, Seattle, WA, USA, [6]Space Science Division, Naval Research Laboratory, Washington, DC, USA, [7]College of Science, George Mason University, Fairfax, VA, USA, [8]Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL, USA

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.



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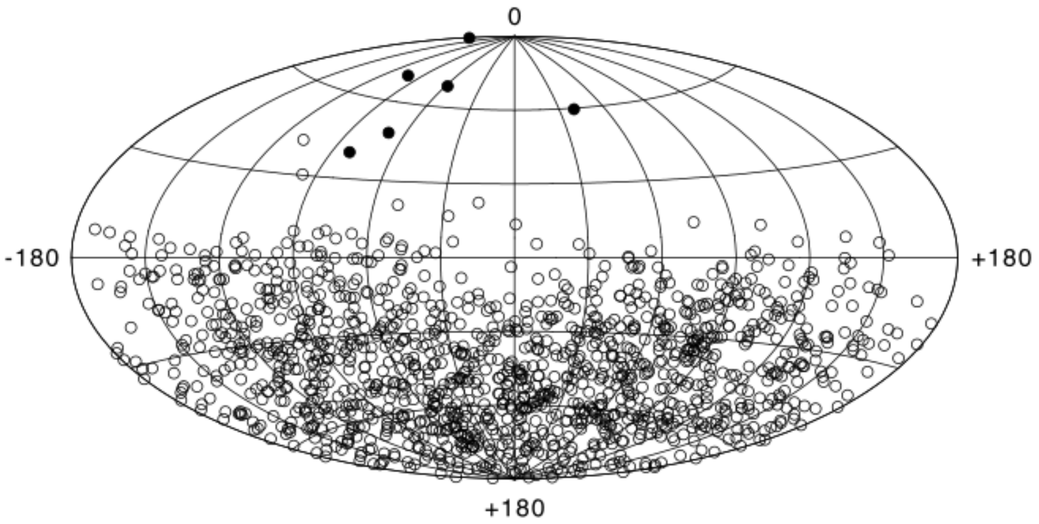
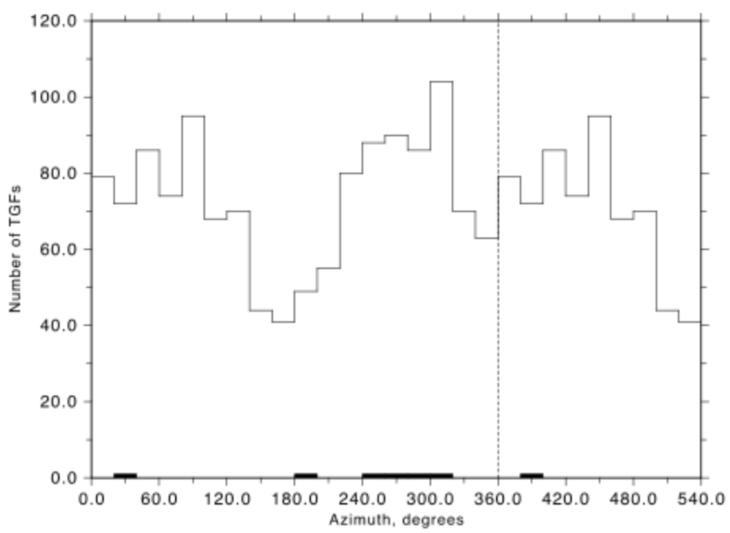
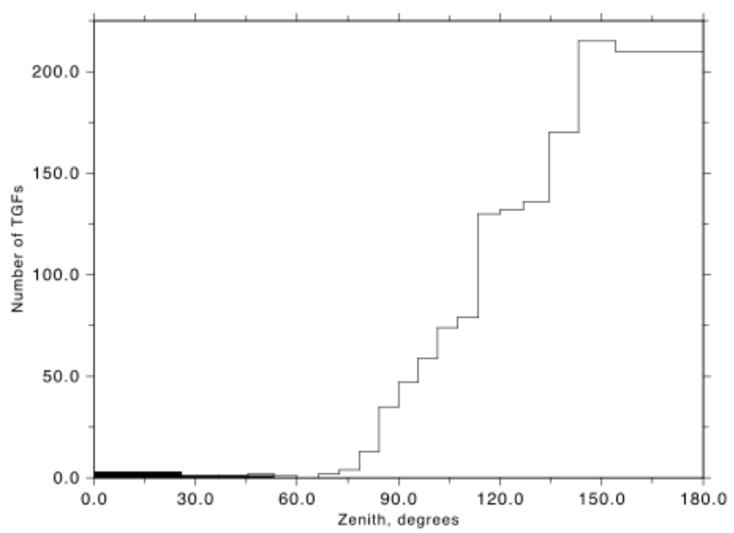
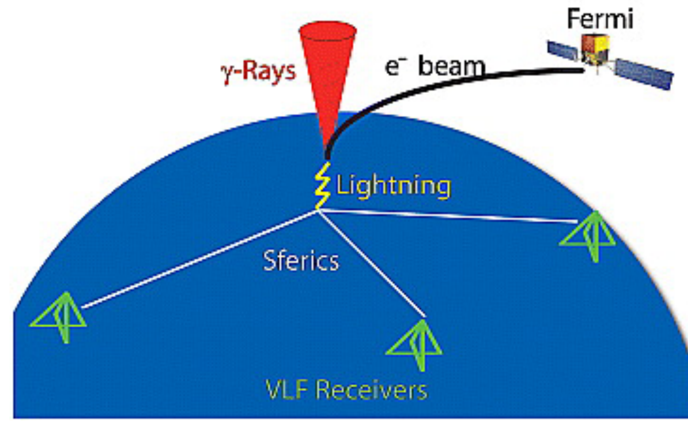


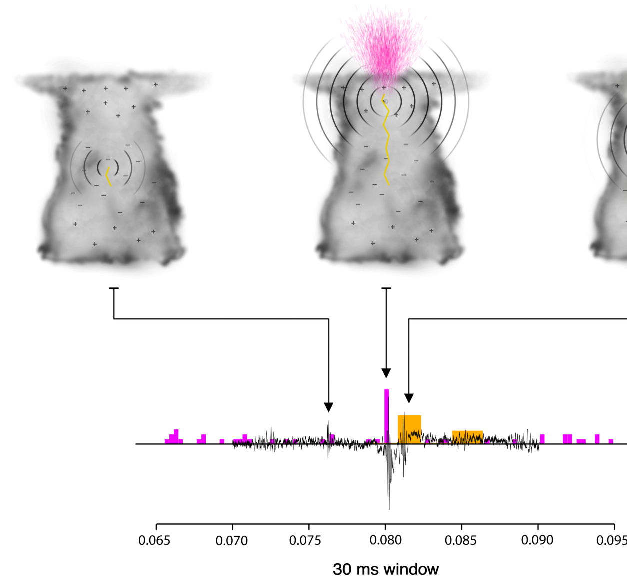




Correlations with VLF

- 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.





Østgaard et al. 2013, GRL 40(10), 2423

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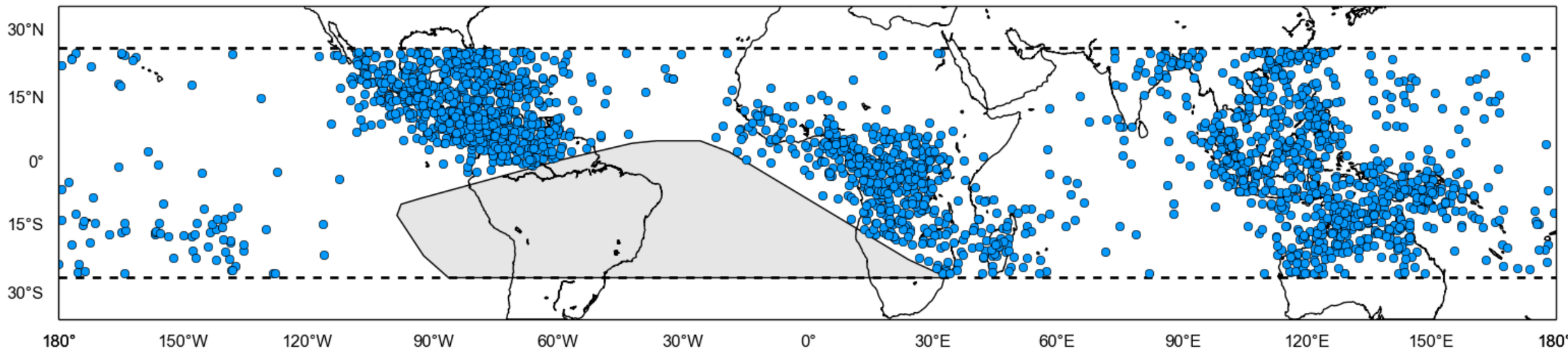
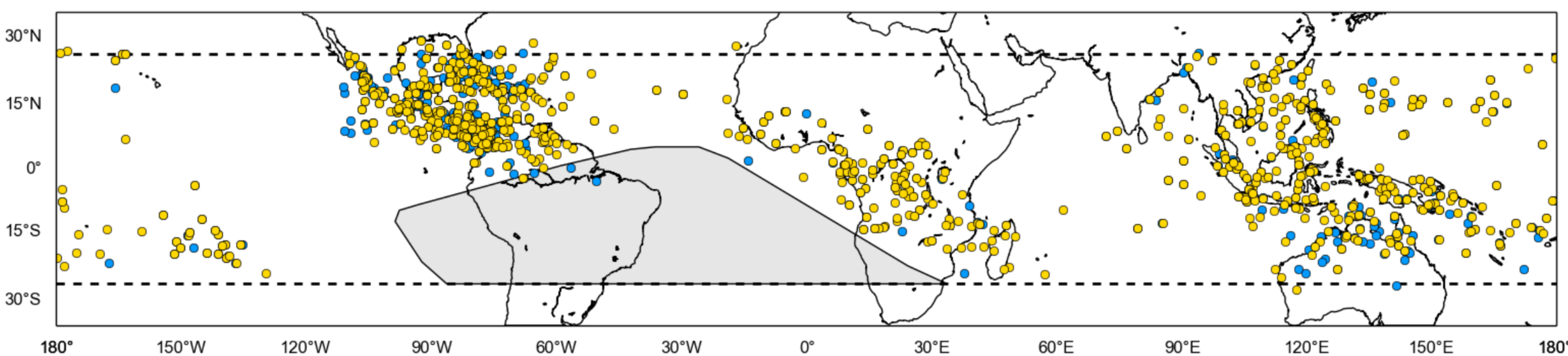
>4000 TGFs (All)



>1300 TGFs (VLF)



Temporal/Geographical Variation

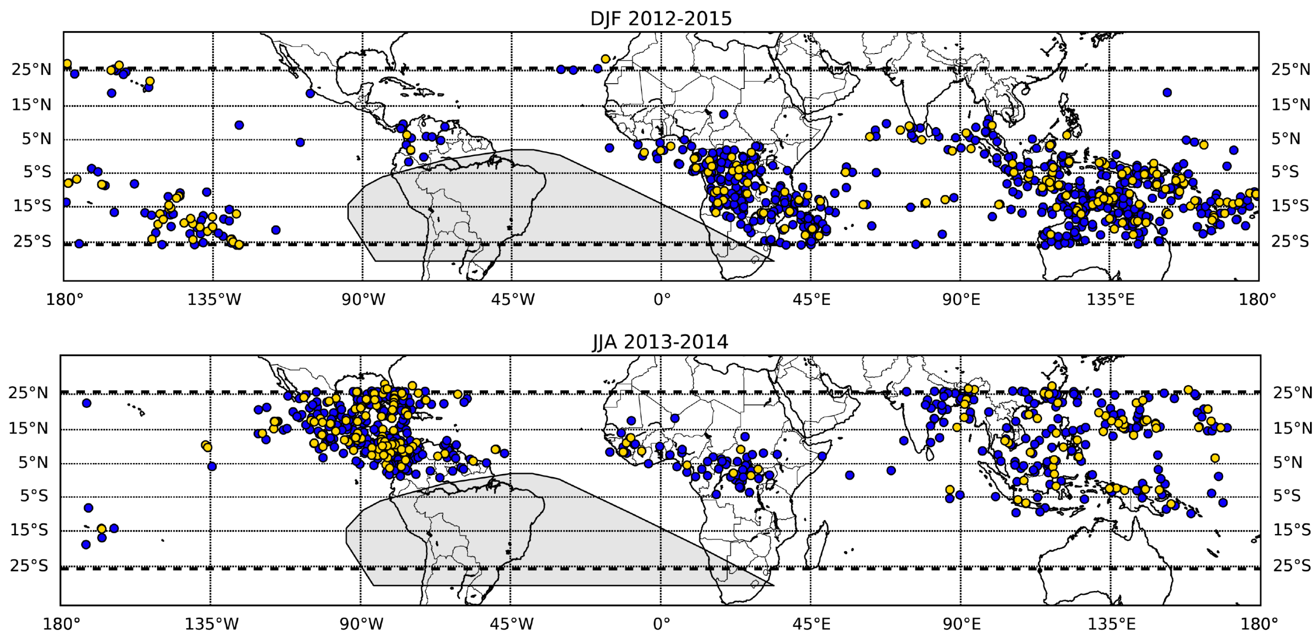
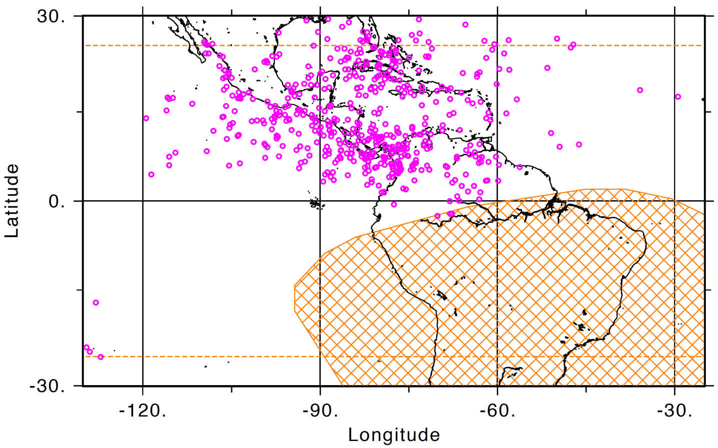
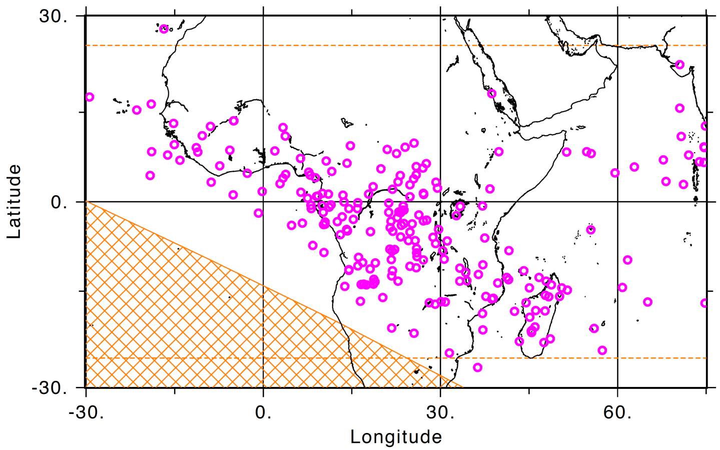
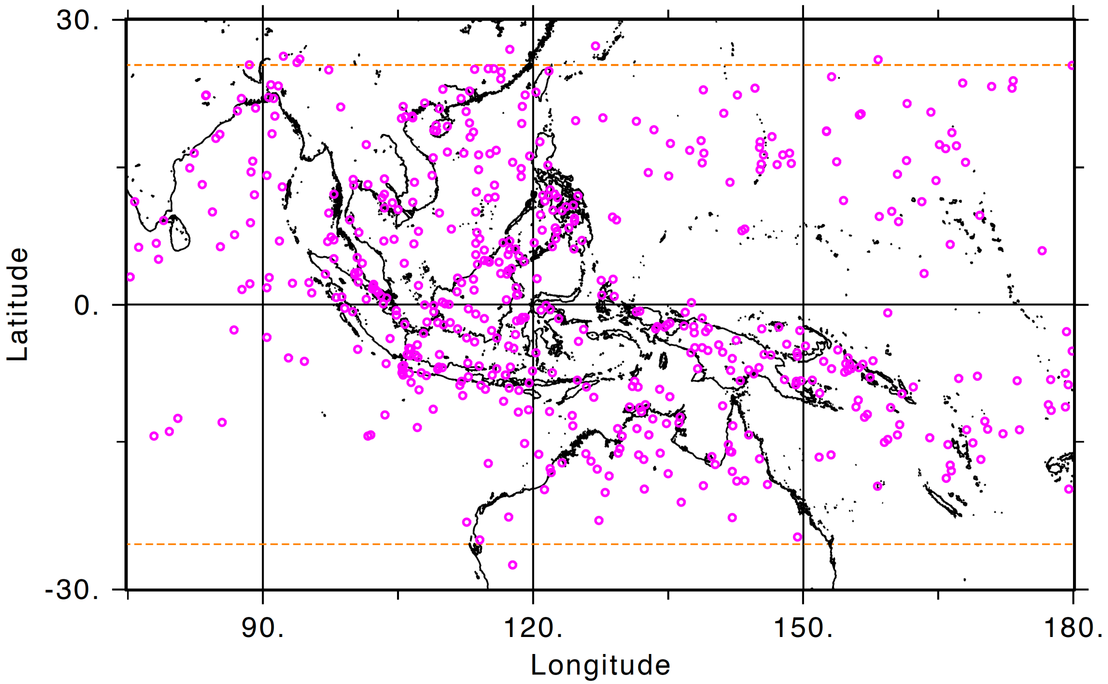


Figure 12. *Top:* Three years of TGF data from the months of December, January and February (DJF). *Bottom:* Two years of TGF data from the months of June, July and August (JJA). *Both Plots:* Blue markers are TGFs without a VLF association, yellow markers denote TGFs with a VLF association. The SAA 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).

Temporal/Geographical Variation







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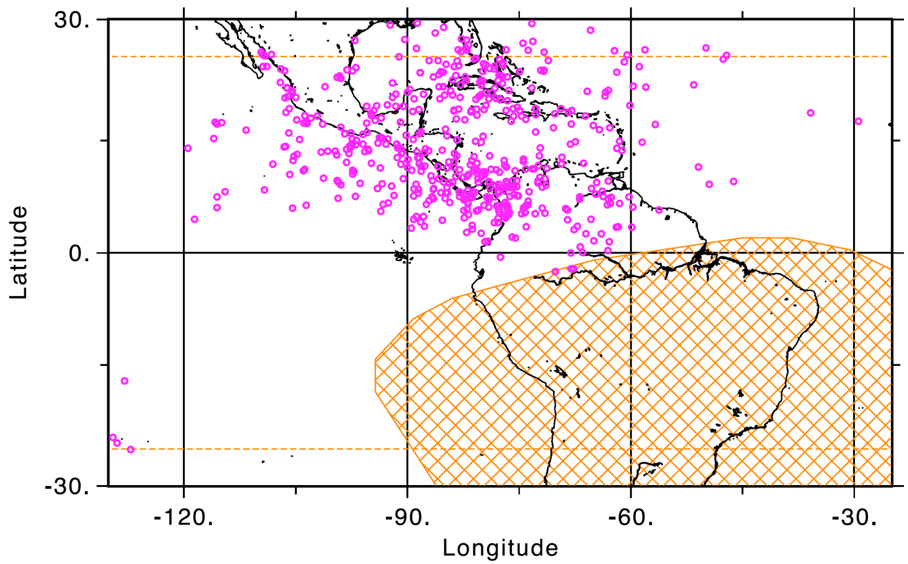
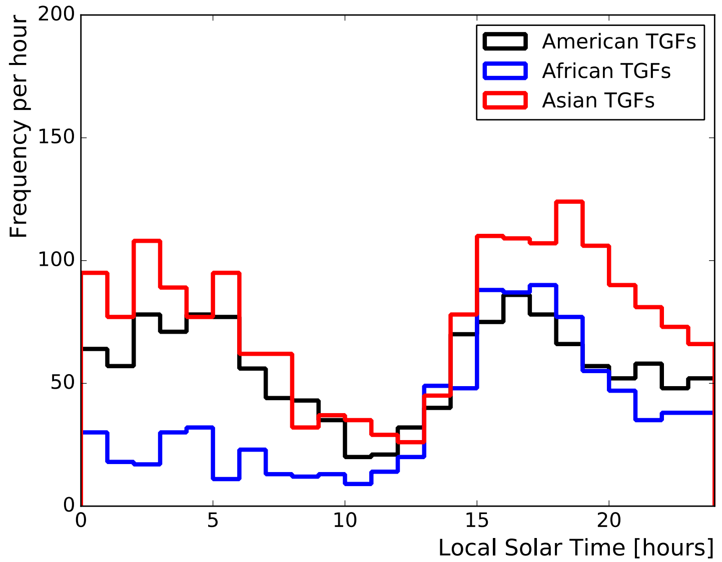
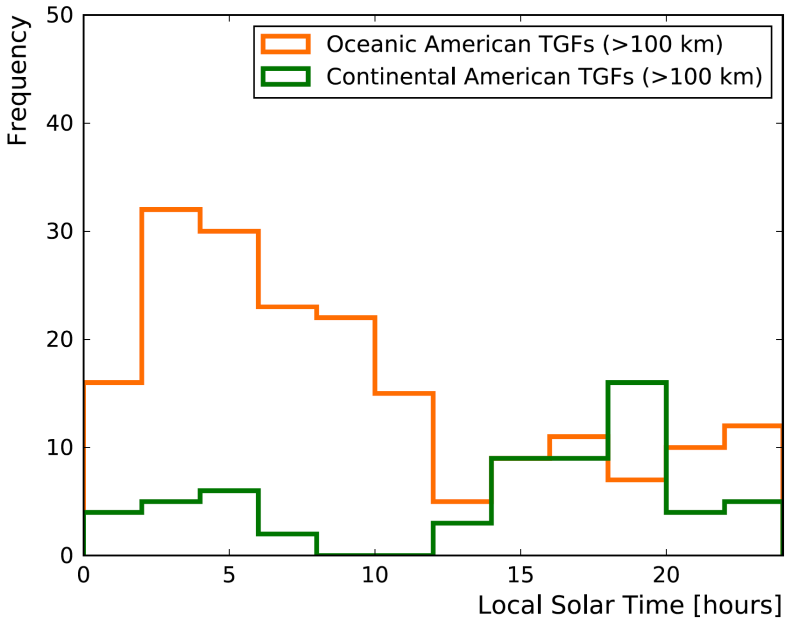
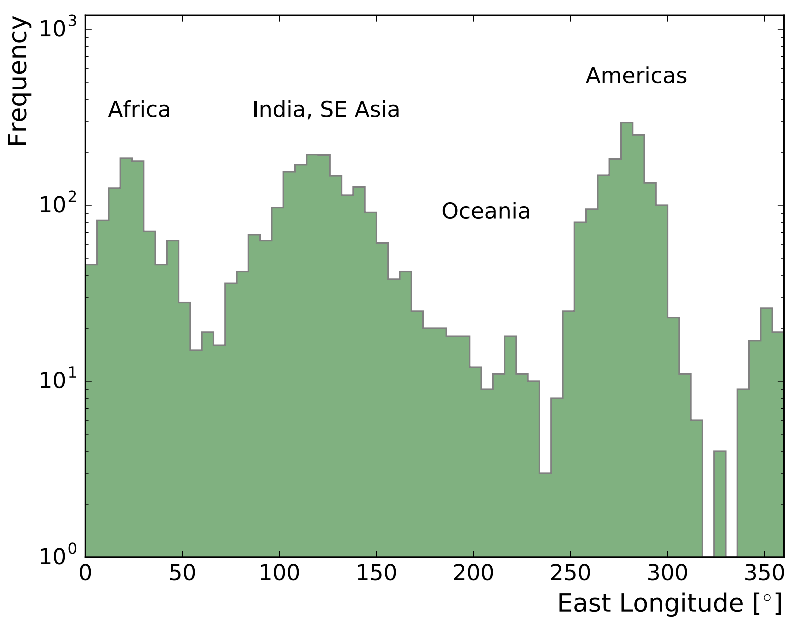
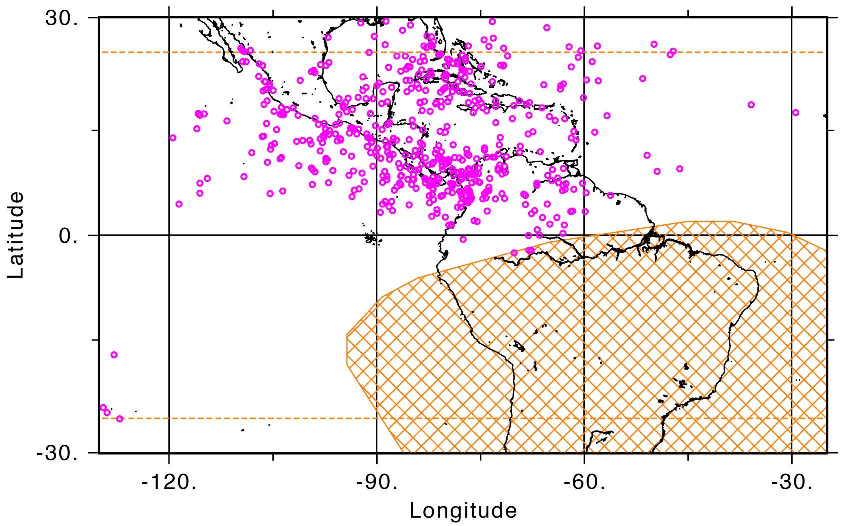


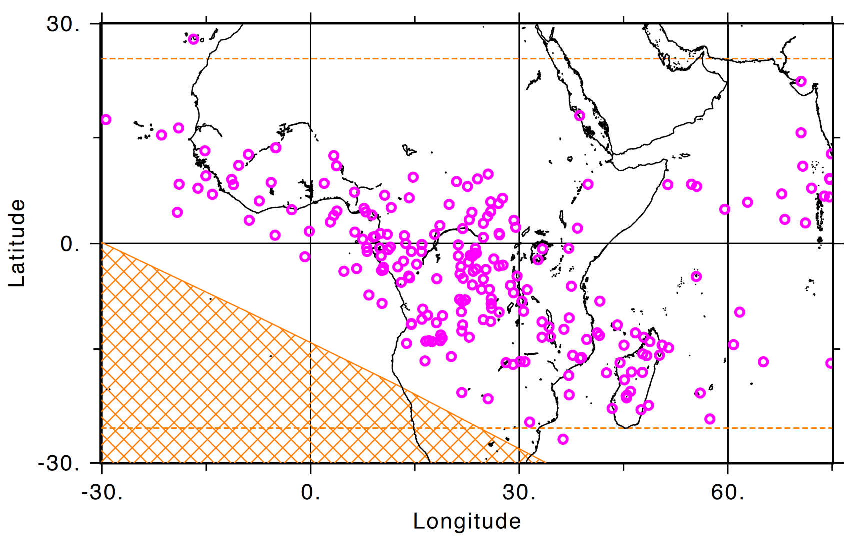




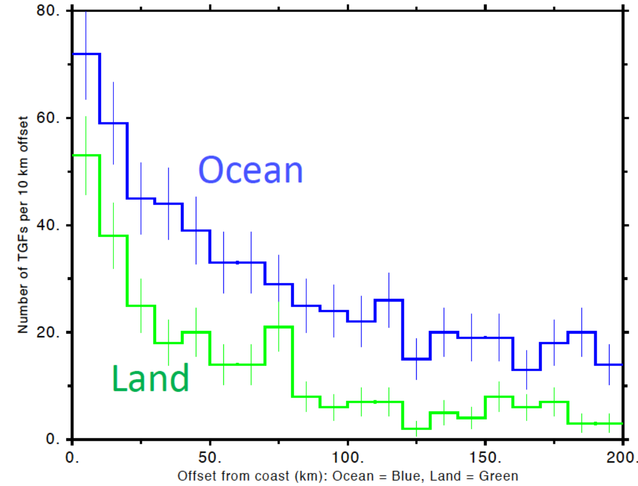


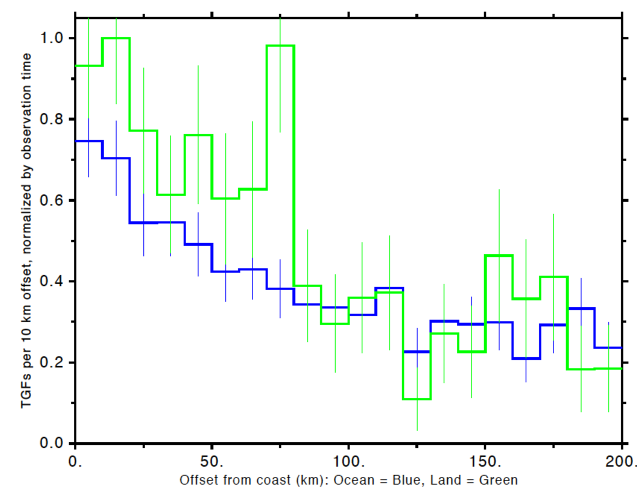
Temporal/Geographical Variation





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.

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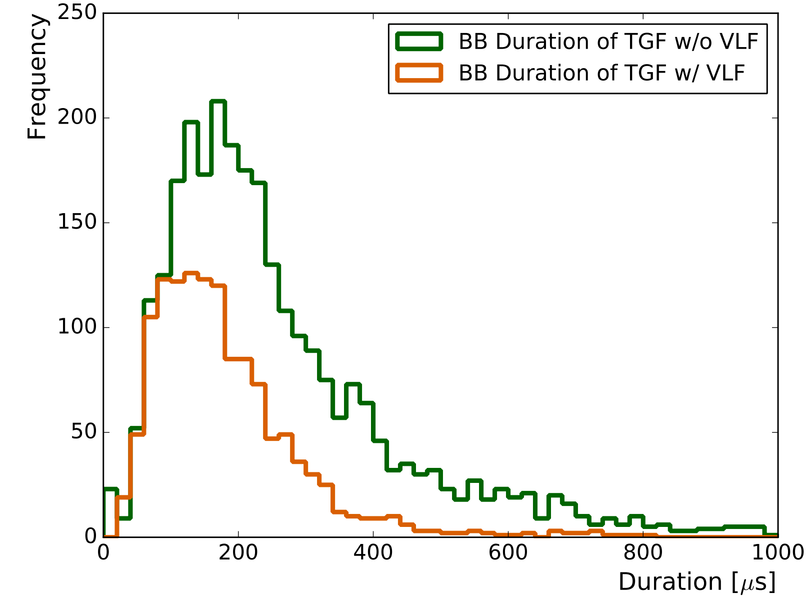
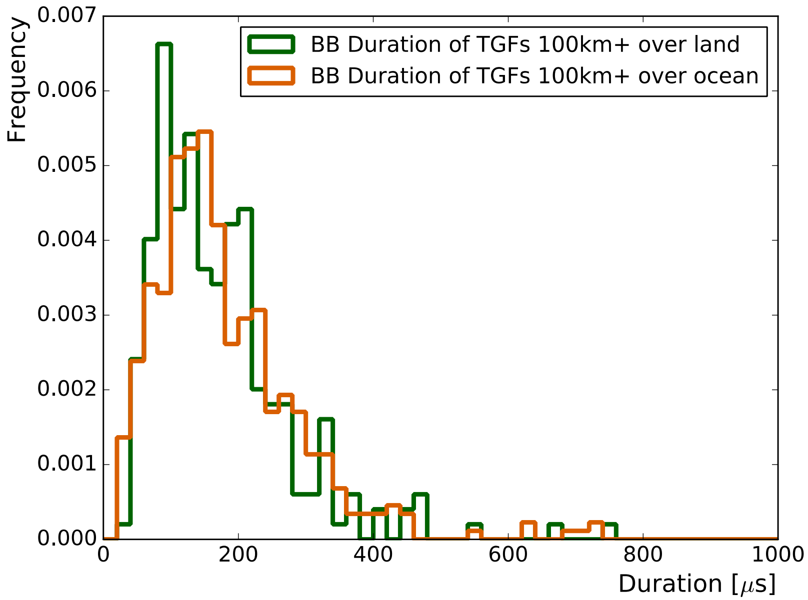
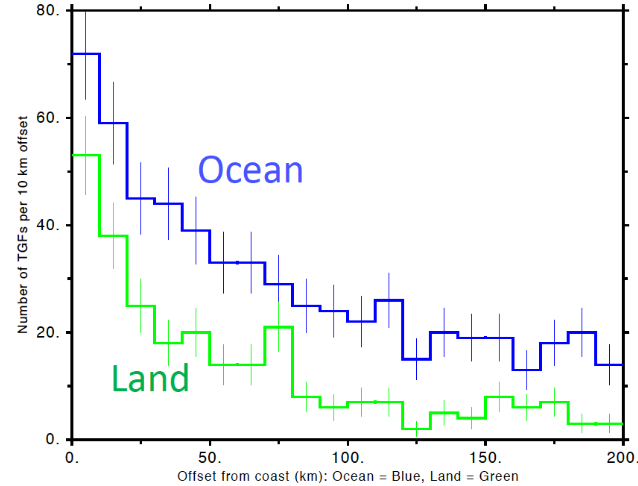
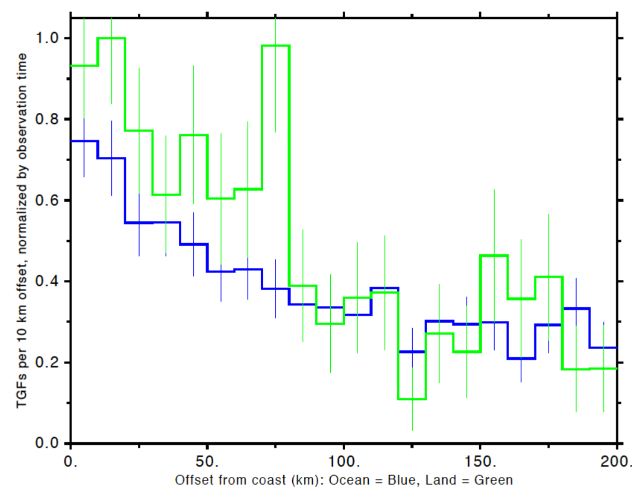




TGF source locations < 200 km of coastline.





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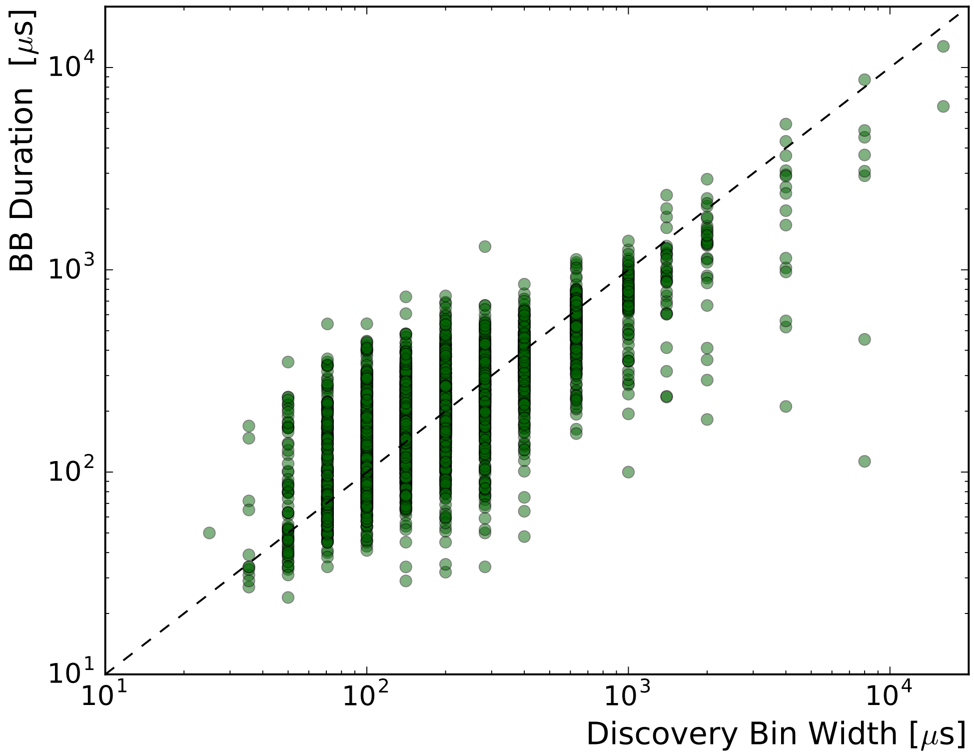
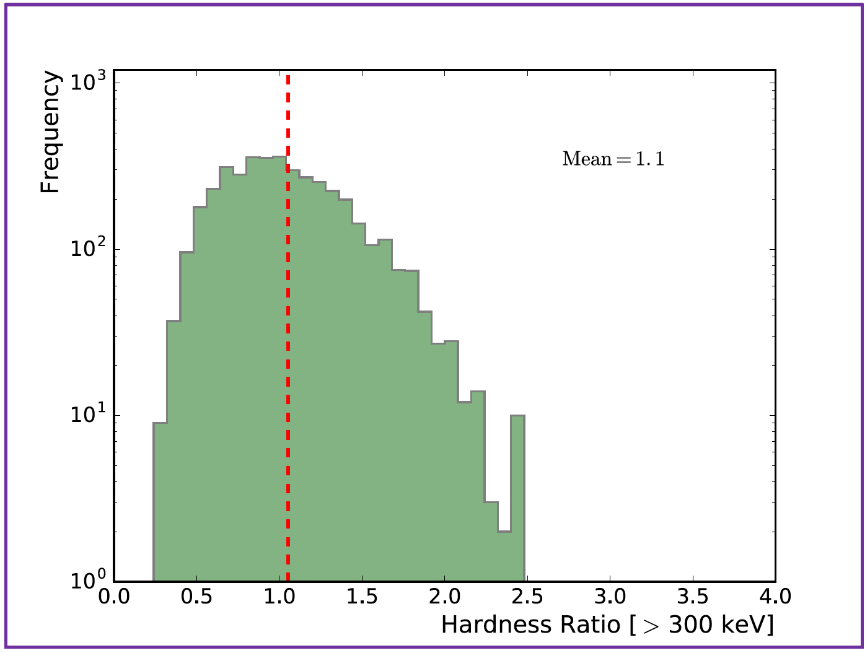
Bayesian Block Analysis





- Hardness Ratio = 316 keV.

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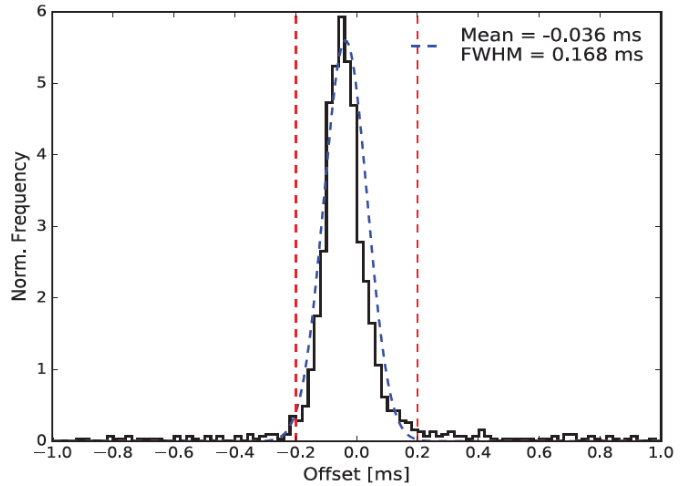
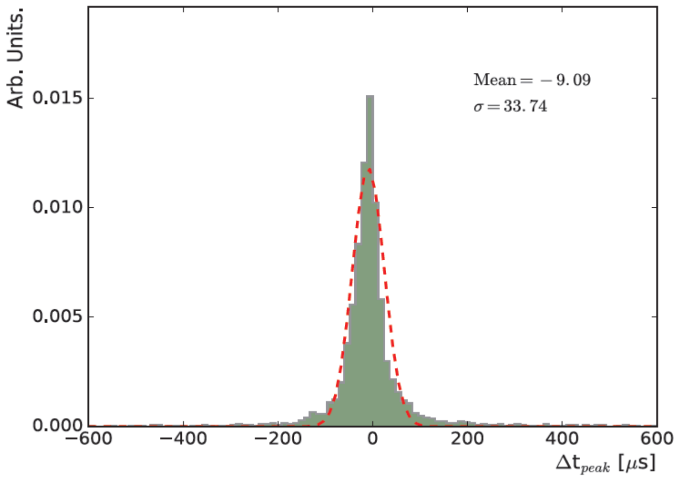
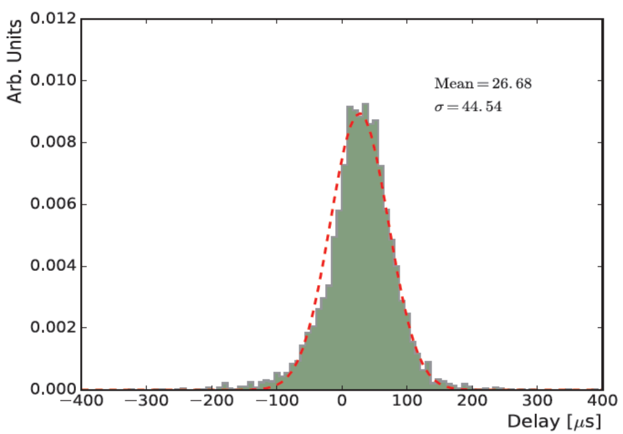


- WWLLN times of group arrival minus the center times of the TGF discovery bins after accounting for light travel time.



- 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*: <u>28+/- 3 μs</u>.
  - *Fitzpatrick, 2014*: <u>24 μs</u> (-20 – 80 μs range).

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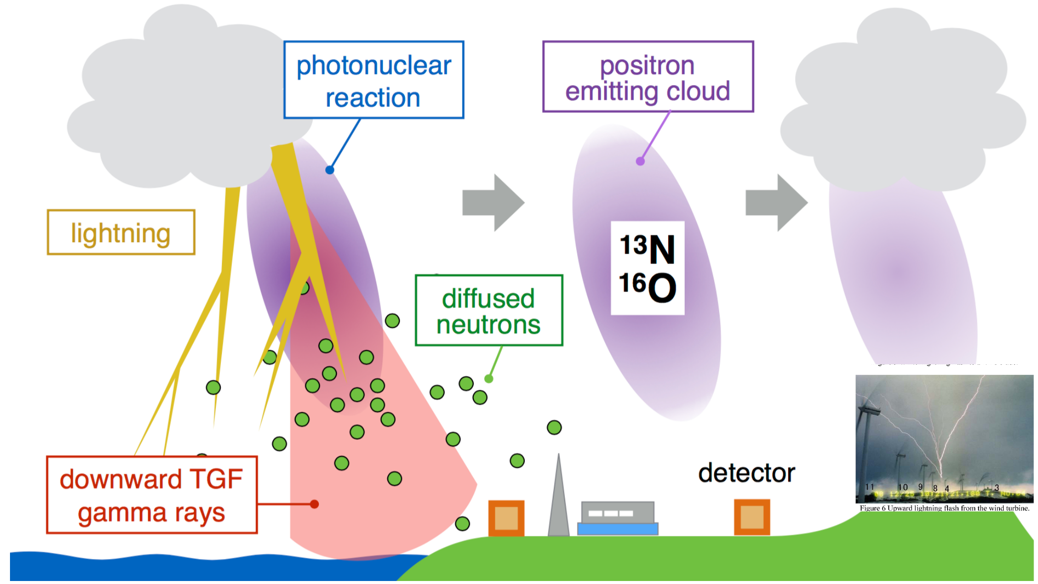
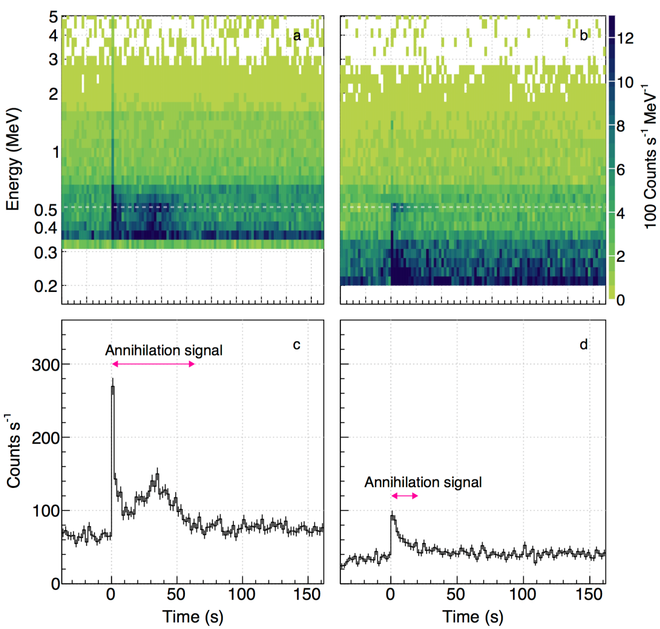
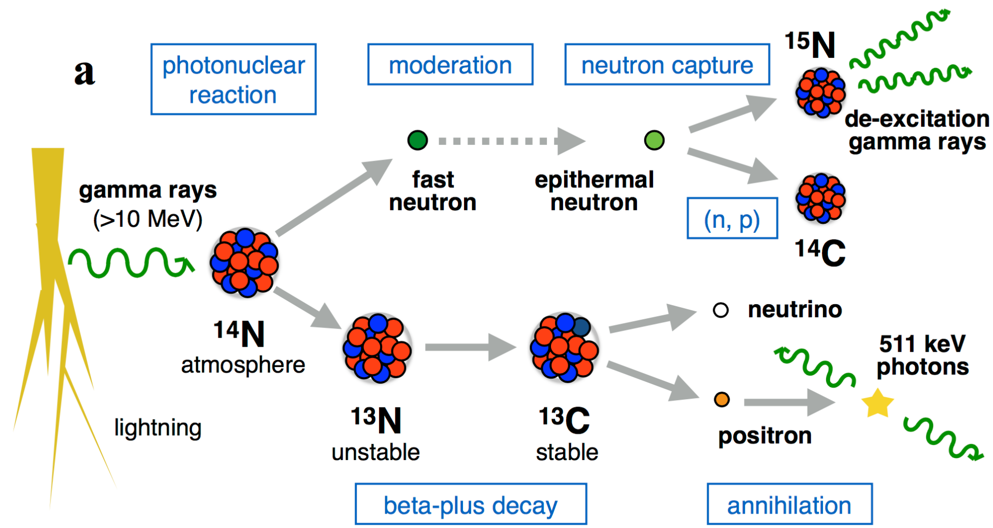
The Future is Bright!
TGF Ground Studies:

- Focus shifting toward neutron detection and more into the photo-nuclear reactions in the atmosphere.
- More TGFs are being observed from the ground at altitudes below 2 km.



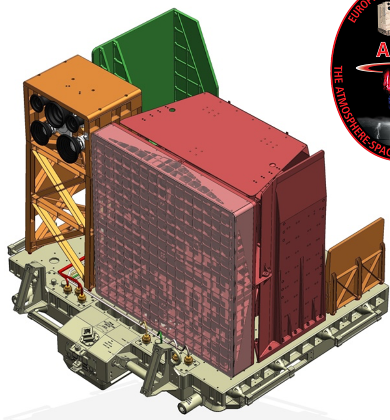


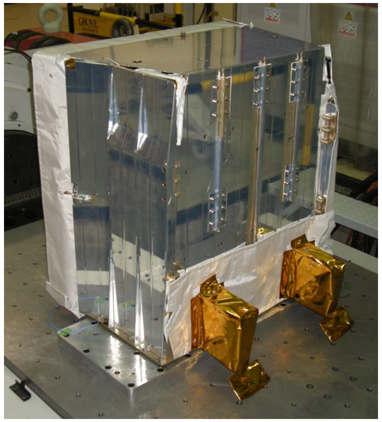


Enoto et al. 2017, Nature, 24630

The Future is Bright!

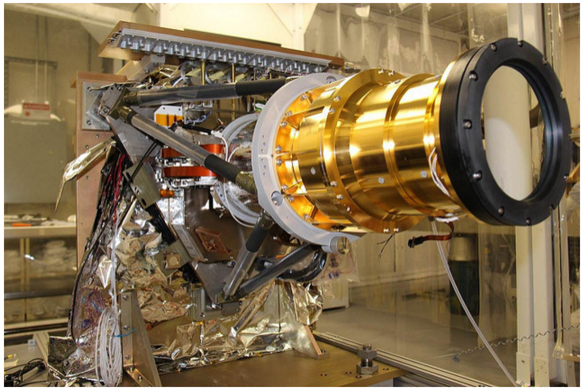
TGF Space-based Studies:





ASIM:

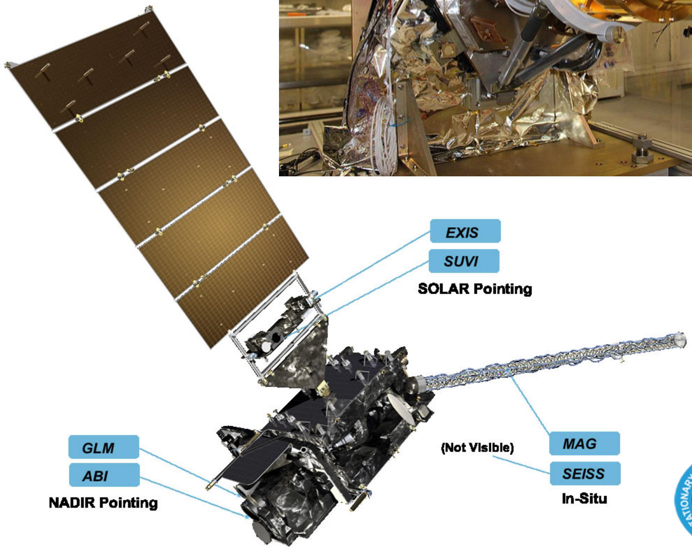
- The ASIM MXGS instrument carries two set of detectors for TGFs; 15 keV to 400 keV and 200 keV to 40 MeV. The low energy detector has 128x128 channels with a high mass density coded mask - Direction to the TGF source.
- Correlation with other instruments (optical imaging by the MMIA instrument, lightning and TLEs).



GLM (GOES-16):

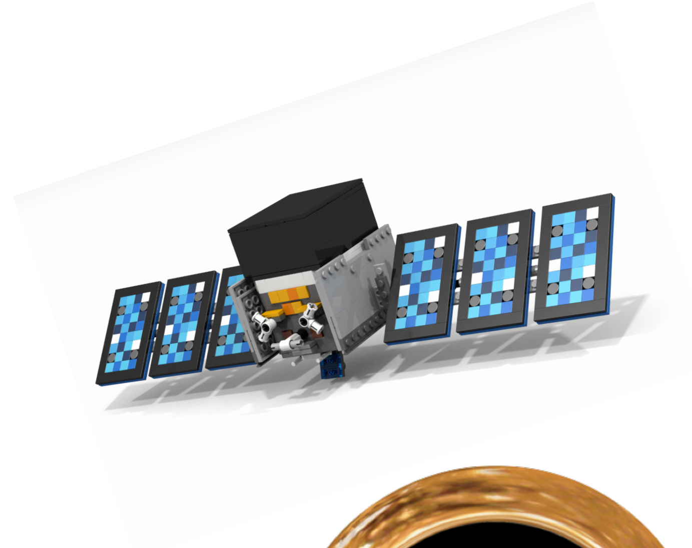
Geostationary Lightning Mapper is a single-channel, near-infrared optical transient detector that can detect the momentary changes in an optical scene, indicating the presence of lightning. GLM measures total lightning (in-cloud, cloud-to-cloud and cloud-to-ground) activity continuously over the Americas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

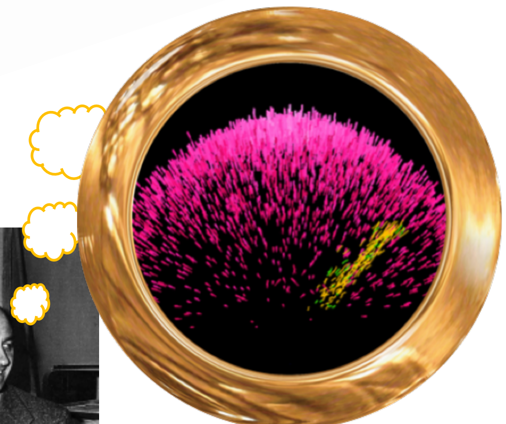
- Staring CCD imager (1372x1300 pixels)
- Near uniform spatial resolution 8 km nadir, 14 km edge fov
- Coverage up to 52 deg N lat
- 0-90% flash detection day and night

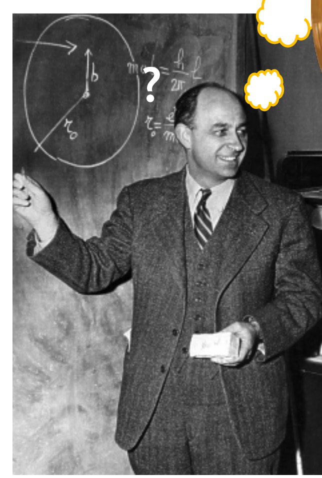


What's next for GBM?

- 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.







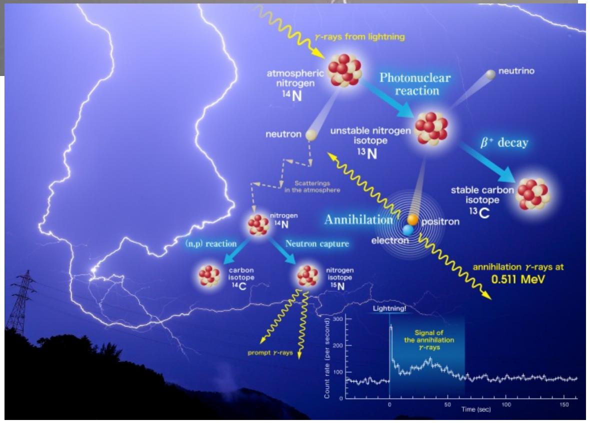
What next for GBM?

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

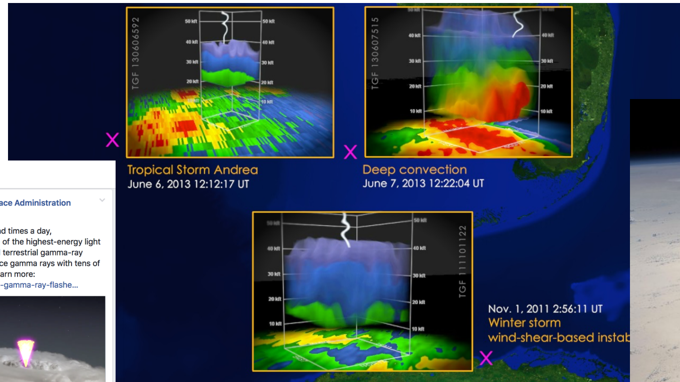
- With the launch of GLM, GBM will undoubtedly help in determining when the TGF occurs during the lightning process with higher certainty – correlations with optical flash (GLM) and radio sferic (WWLLN) - Complete EM picture.

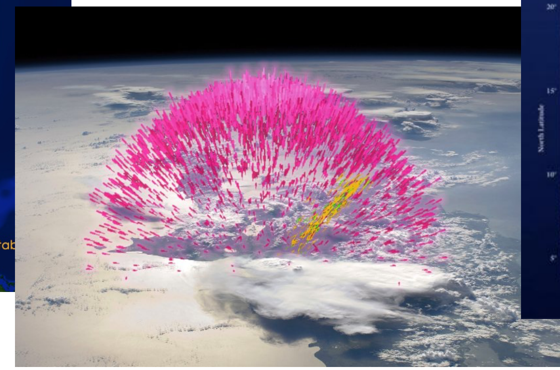
This will help narrow existing initiation mechanism models!

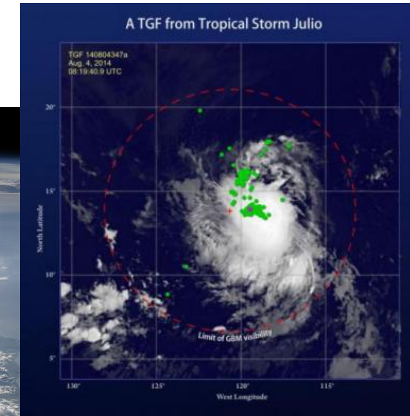
- Future projects involving multiple radiation detection to look in–detail at the photo-nuclear reactions that occur in the sky.

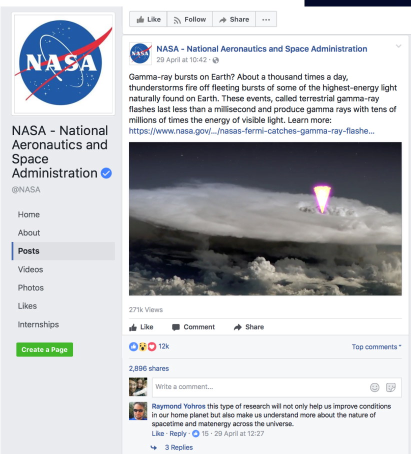


GBM-TGF Group









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NASA - National Aeronautics and Space Administration
29 April at 10:42

Gamma-ray bursts on Earth? About a thousand times a day, thunderstorms fire off fleeting bursts of some of the highest-energy light naturally found on Earth. These events, called terrestrial gamma-ray flashes last less than a millisecond and produce gamma rays with tens of millions of times the energy of visible light. Learn more: https://www.nasa.gov/.../nasas-fermi-catches-gamma-ray-flashe...

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Raymond Yohros this type of research will not only help us improve conditions in our home planet but also make us understand more about the nature of spacetime and matenergy across the universe.
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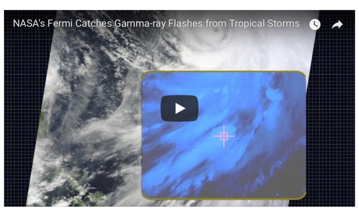
3 Replies

Happy Birthday Fermi!



SCIENCE NEWS APRIL 24, 2017 / 5:02 PM

Scientists study terrestrial gamma-ray flashes produced by tropical storms

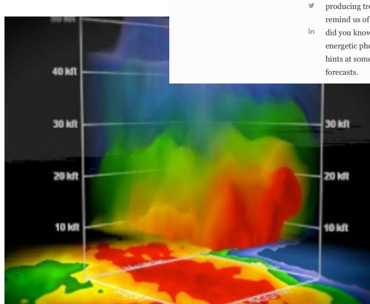
As tropical systems grow in size and strength, their clouds are pushed higher into the atmosphere where intense electrical fields can develop, yielding terrestrial gamma-ray flashes.

By Brooks Hays

NASA's Fermi Catches Gamma-ray Flashes from Tropical Storms

April 24 (UPI) -- For the first time, researchers have analyzed terrestrial gamma-ray flashes produced by tropical storms. Terrestrial gamma-ray flashes, or TGFs, are one of 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 a millisecond and produce several million times the energy of natural light. Until now, scientists hadn't studied flashes produced by tropical storms, hurricanes or typhoons.



Forbes

Billionaires Innovation Leadership Money Consumer Industry

EDITOR'S PICK | 3,637 views | Jun 21, 2017, 12:52pm

Hurricanes Have Something In Common With Black Holes - They Produce Gamma Rays

Marshall Shepherd Contributor
Science

Atmospheric scientists like me are closely monitoring the tropics at this time of year. Tropical Storm Cindy in the Gulf of Mexico is producing tremendous rainfall totals and tornado threats that remind us of the many things that a hurricane can produce. However, did you know that hurricanes can produce one of nature's more energetic phenomena, gamma rays? A new study explains how and hints at some possible value for improving hurricane intensity forecasts.

.ORG Nanotechnology Physics Earth Astronomy & Space Technology Chemistry

Earth Sciences · April 24, 2017

Fermi catches gamma-ray flashes from tropical storms

April 24, 2017 by Francis Reddy

During a period of rapid strengthening on Aug. 23, 2012, Typhoon Bolaven launched its only TGF from an outer rain band located nearly 490 miles (785 km) from the storm's center (roughly bottom center of the full image). The Moderate ... more

About a thousand times a day, thunderstorms fire off fleeting bursts of some of the highest-energy light naturally found on Earth. These events, called terrestrial gamma-ray flashes (TGFs), last less than a millisecond and produce gamma rays with tens of millions of times the energy of visible light. Since its launch in 2008, NASA's Fermi Gamma-ray Space Telescope has recorded more than 4,000 TGFs, which scientists are studying to better understand how the phenomenon relates to lightning activity, storm strength and the life cycle of storms.

Now, for the first time, a team of NASA scientists has analyzed dozens of TGFs launched by the largest and strongest weather systems on the planet: tropical storms, hurricanes and typhoons. A paper describing the research was published March 16 in the *Journal of Geophysical Research: Atmospheres*.

"One result is a confirmation that storm intensity alone is not the key factor for producing TGFs," said Oliver Roberts, who led the study at the University College Dublin, Ireland, and is now at NASA's Marshall Space Flight Center in Huntsville, Alabama. "We found a few TGFs were made in the outer rain bands of major storms, hundreds of kilometers from the powerful eye walls at their centers, and one weak system that fired off several TGFs in a day."

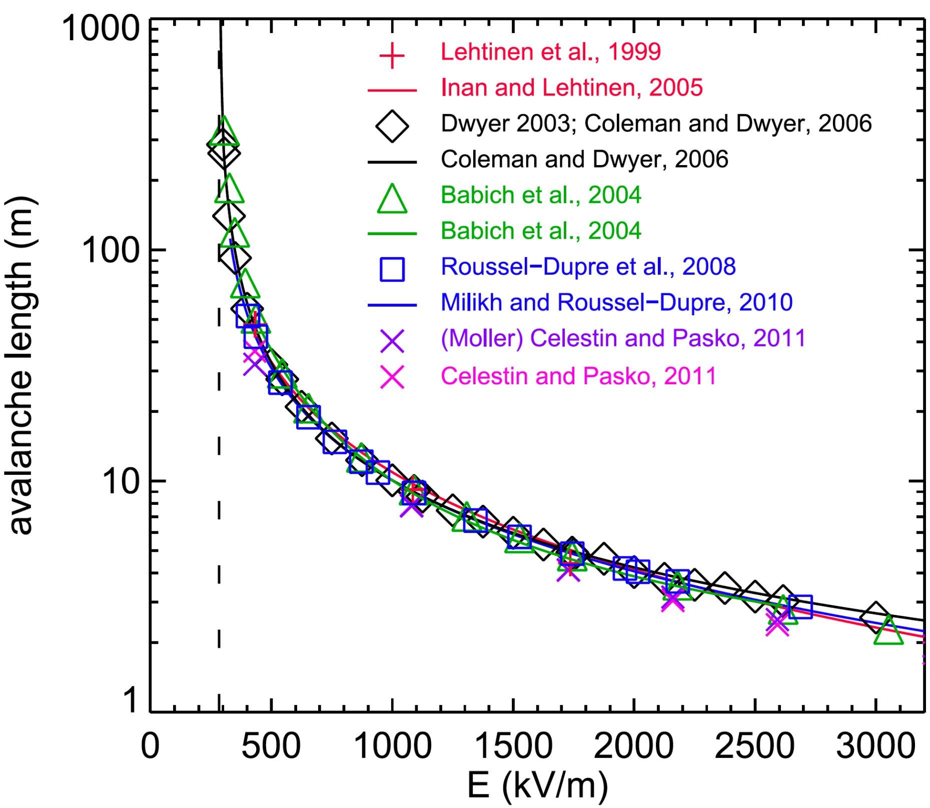
Scientists suspect TGFs arise from the strong electric fields near the tops of thunderstorms. Under certain conditions, these fields become strong enough to drive an "avalanche" of electrons upward at nearly the speed of light. When these accelerated electrons race past air molecules, their paths become deflected slightly. This change causes the electrons to emit gamma rays.

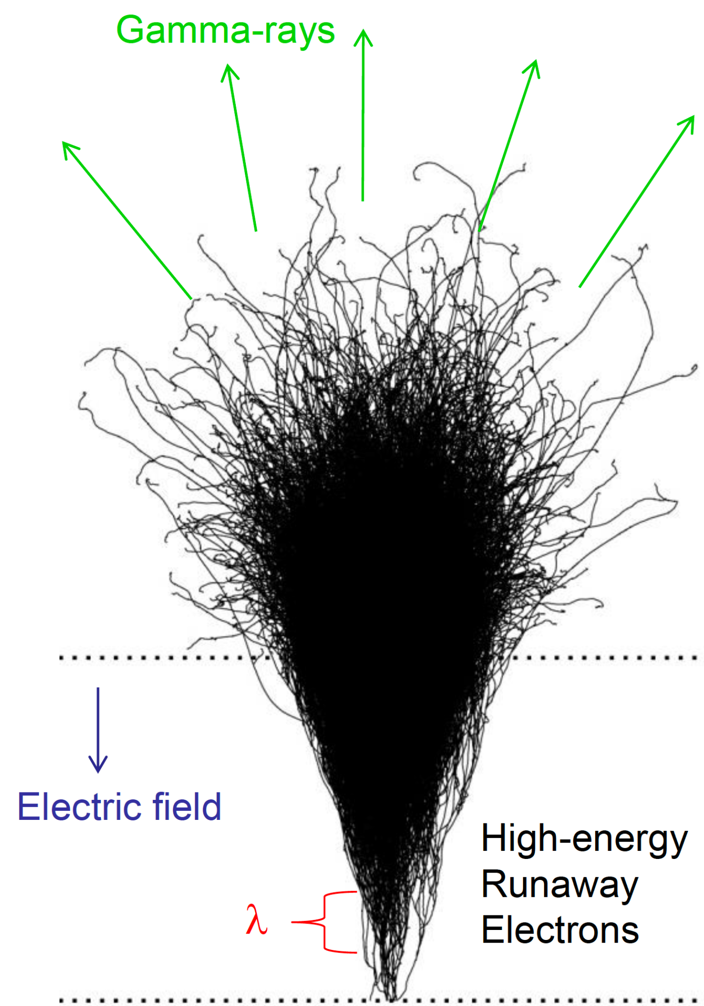

EXTRAS

Relativistic Runaway Electron Avalanches (RREAs)

Gurevich et al. (1992)

The avalanche length, λ, is the e-folding length.

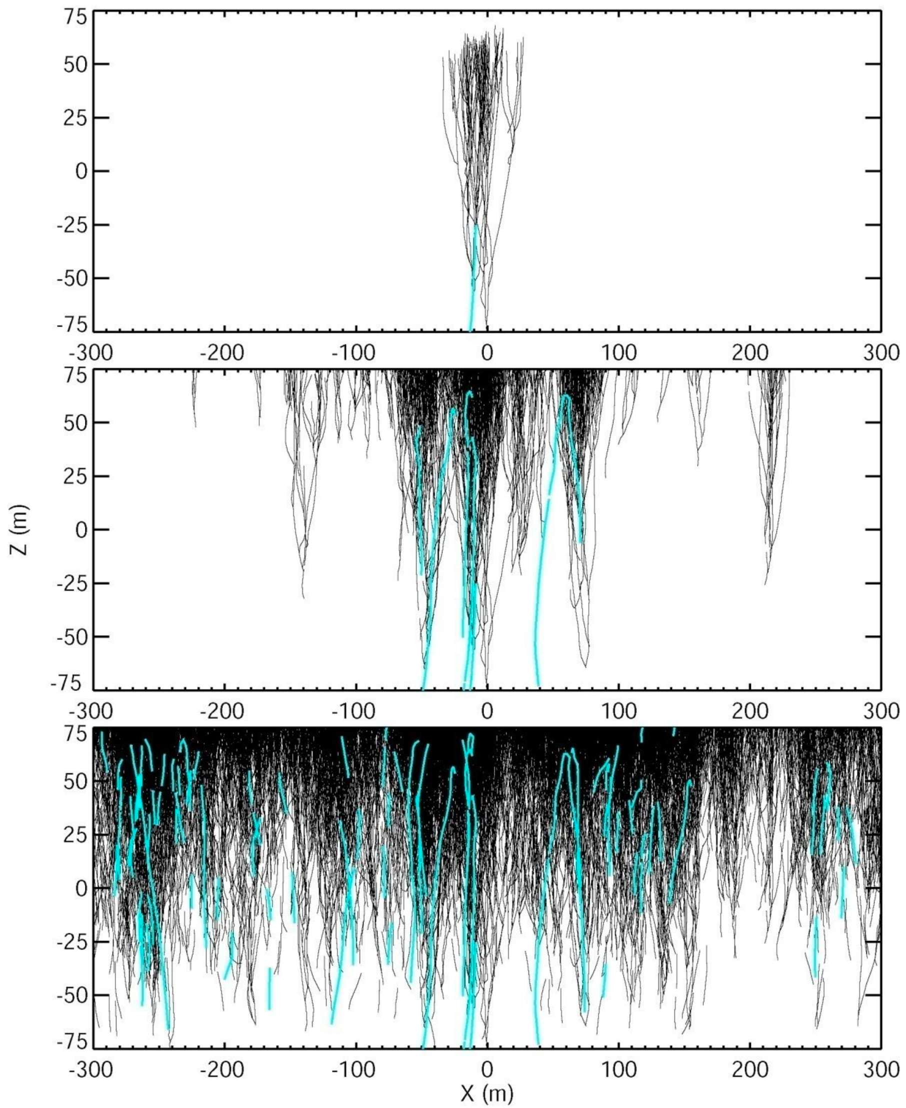




From Dwyer et al. (2012)

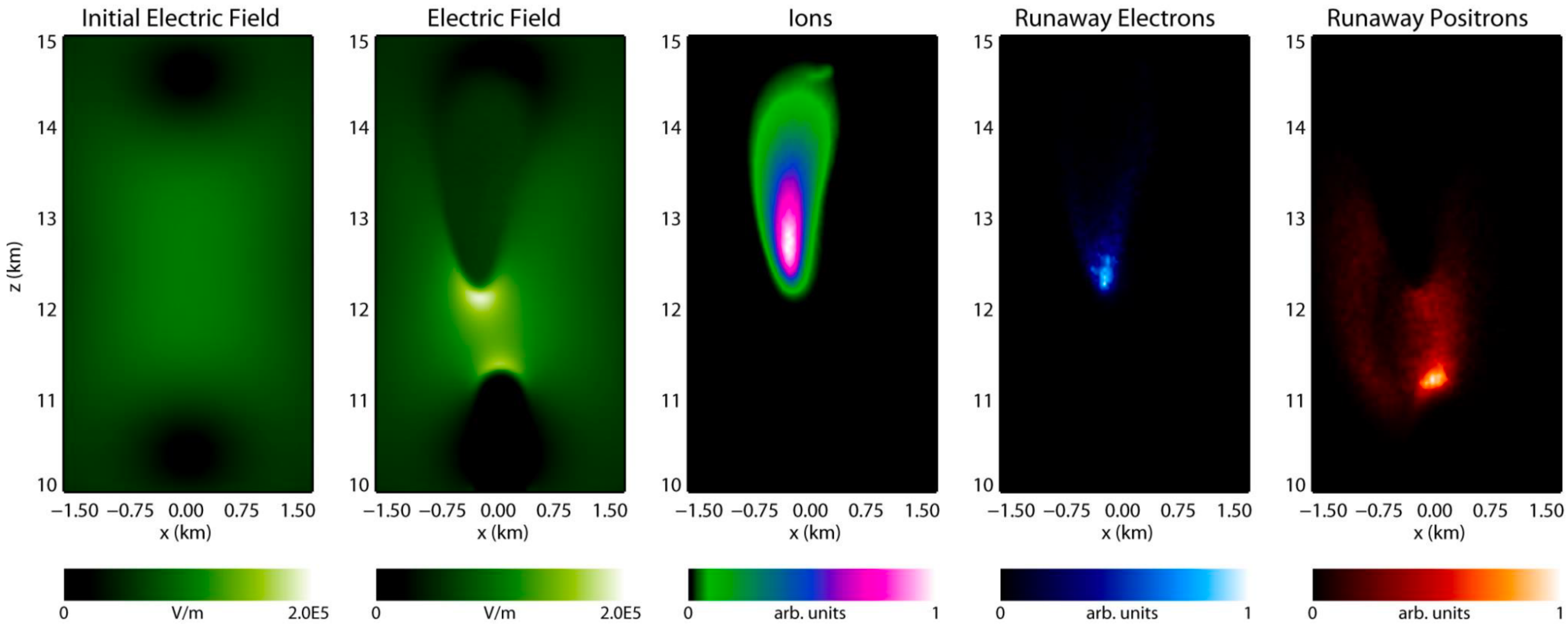
Relativistic feedback discharge (RFD)
aka "Dark Lightning"
due to x-rays and positrons.

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.

GBM-TGF Group

- 37 TGFs found using WWLLN and ENTLN VLF associations.
- TGFs come predominately from strengthening phase of storm.
- Oceanic lightning may be prolific TGF producer.

http://onlinelibrary.wiley.com/doi/10.1002/2016JD025799/epdf

AGU PUBLICATIONS
JGR
Journal of Geophysical Research: Atmospheres

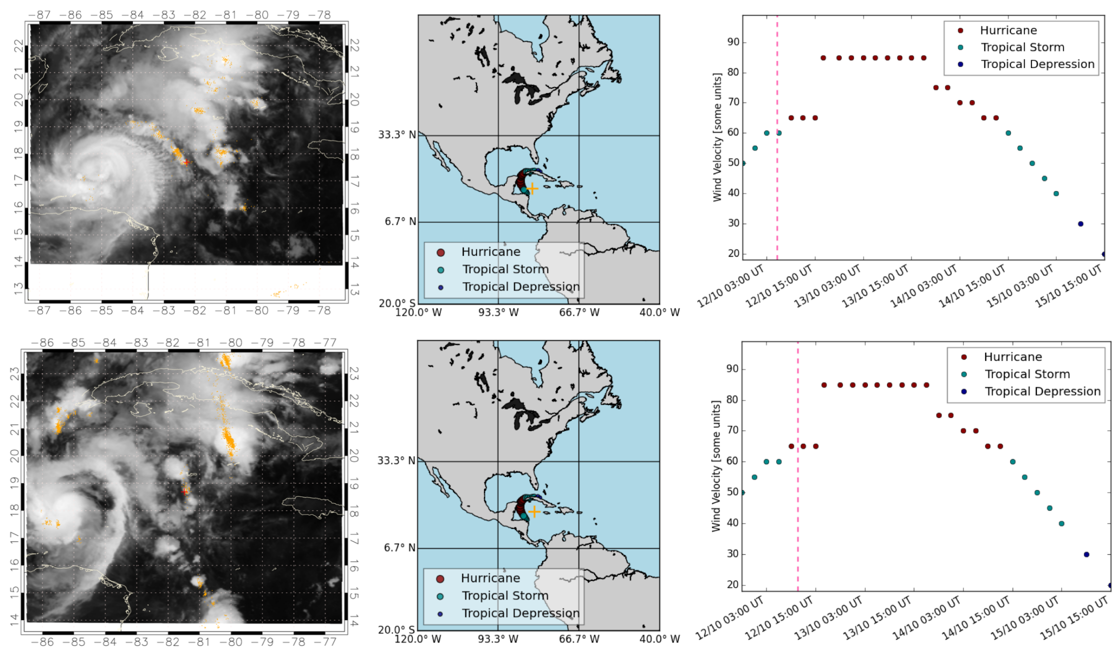
RESEARCH ARTICLE
10.1002/2016JD025799

Key Points:
- TGF production appears to closely follow when/where lightning occurs in tropical storm systems
- Characteristics of TGFs from tropical storm systems appear similar to those produced by other storms
- TGF/sferic ratios may imply a high efficiency of TGF generation from lightning in some storms

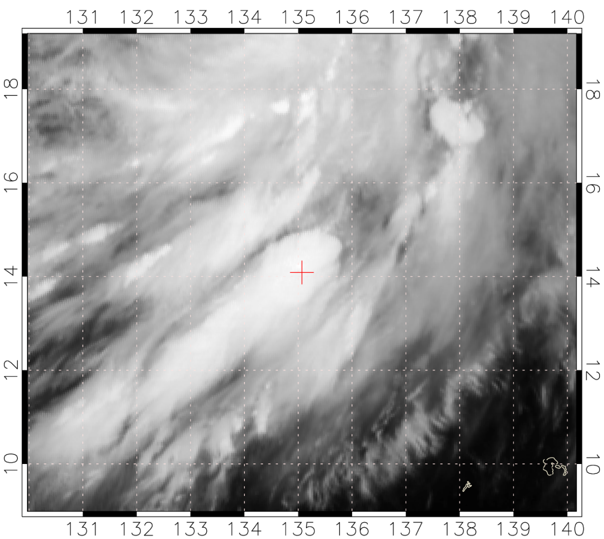
Terrestrial gamma ray flashes due to particle acceleration in tropical storm systems

O. J. Roberts[1], G. Fitzpatrick[1,2], G. Priftis[3], K. Bedka[4], T. Chronis[3], S. McBreen[1], M. S. Briggs[2], E. Cramer[2], B. Mailyan[2], and M. Stanbro[2]

[1]School of Physics, University College Dublin, Belfield, Ireland, [2]CSPAR, University of Alabama in Huntsville, Huntsville, Alabama, USA, [3]ESSC, University of Alabama in Huntsville, Huntsville, Alabama, USA, [4]NASA Langley Research Center, Hampton, Virginia, USA



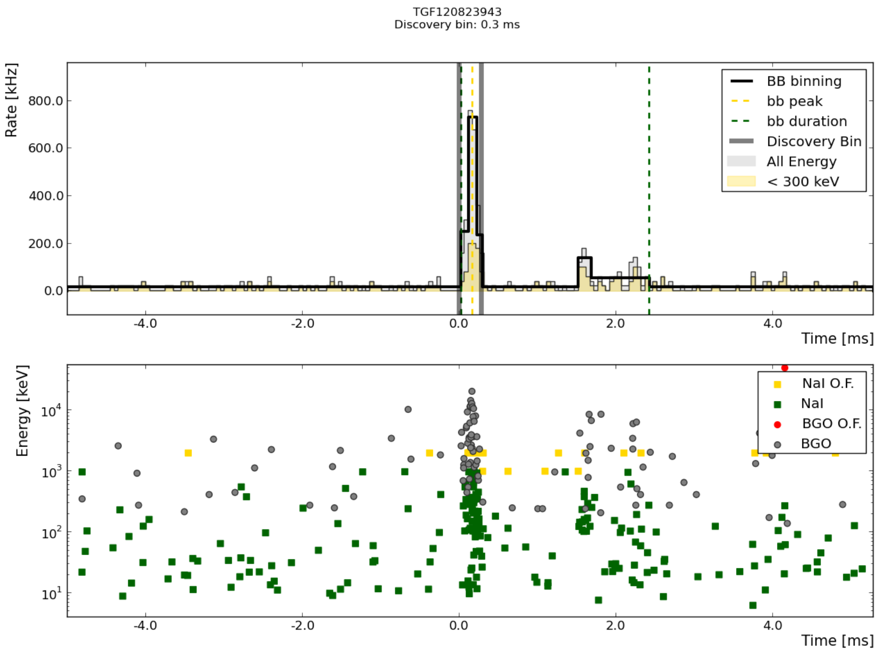
GBM-TGF Group

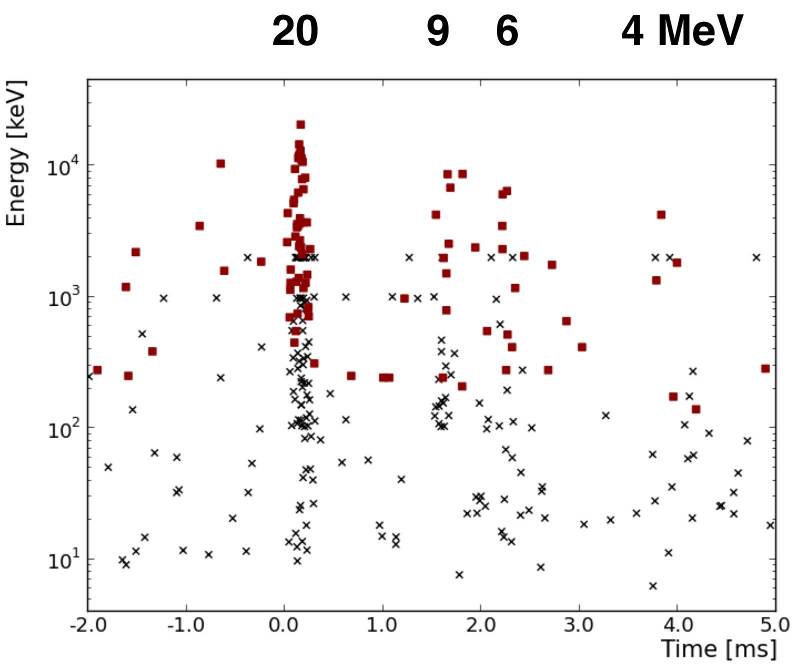


TGF is ~600 km from land & ~800 km from storm-center.

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

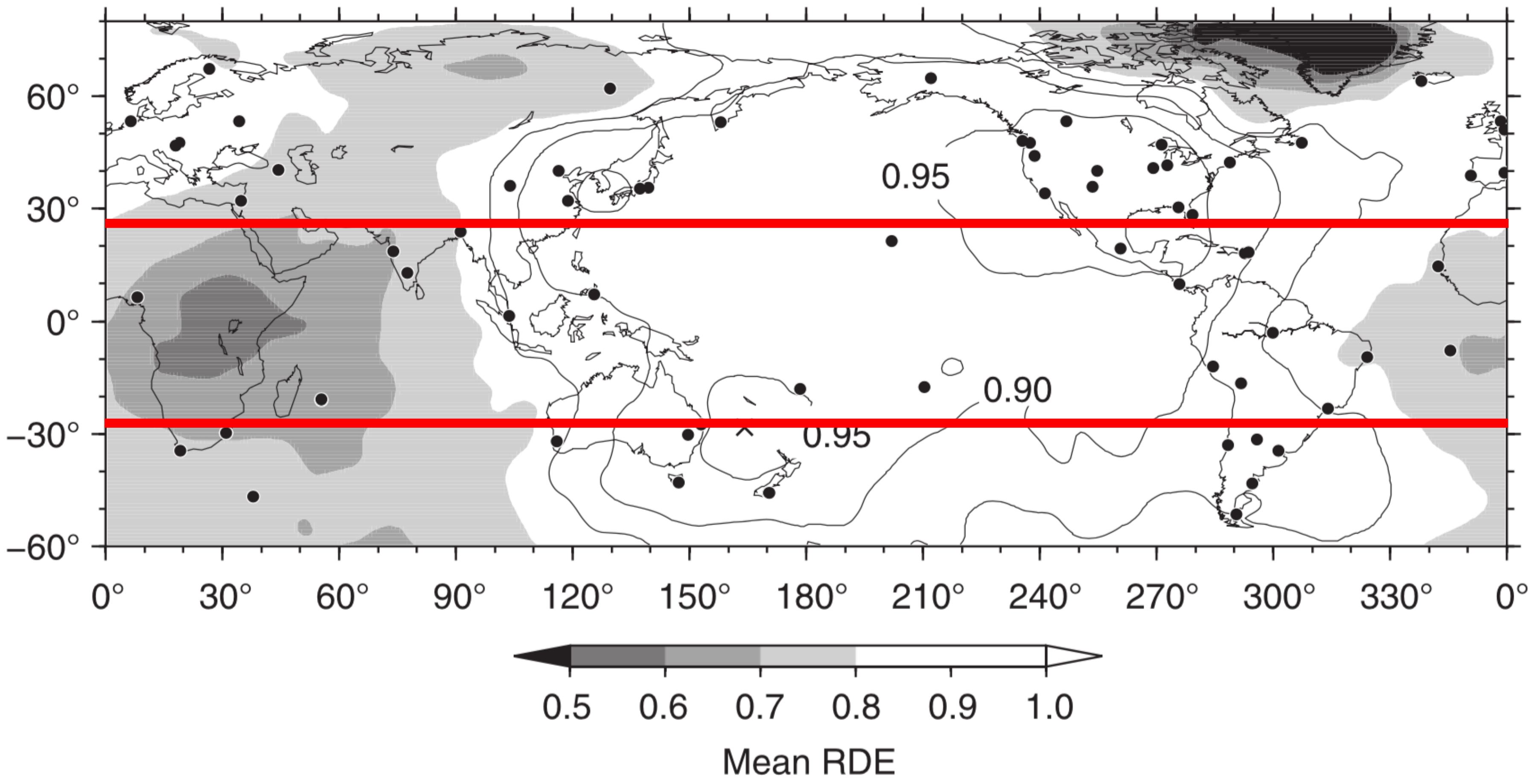
4 pulses over 4 ms. First pulse had a sferic association, unlike observations by Mezentsev et al., 2016



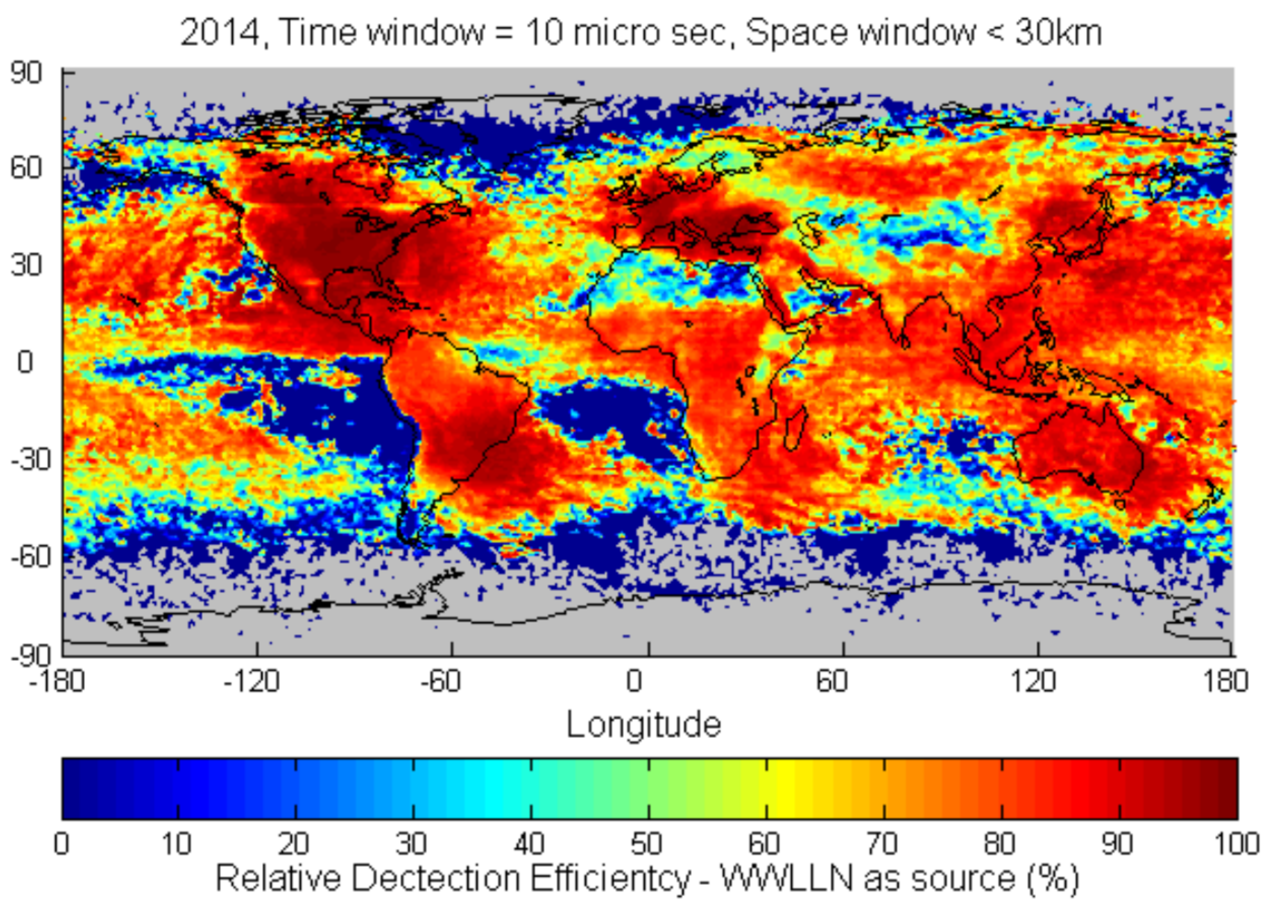


WWLLN Detection Efficiency

H. Iwasaki, Int. J. Climatol. 35: 4337–4347 (2015), DOI: 10.1002/joc.4291



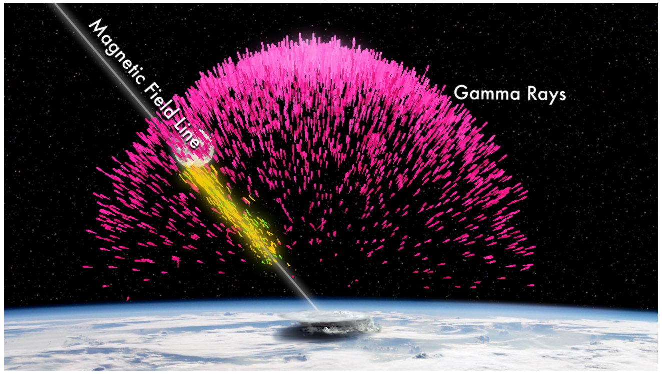
ENTLN Detection Efficiency

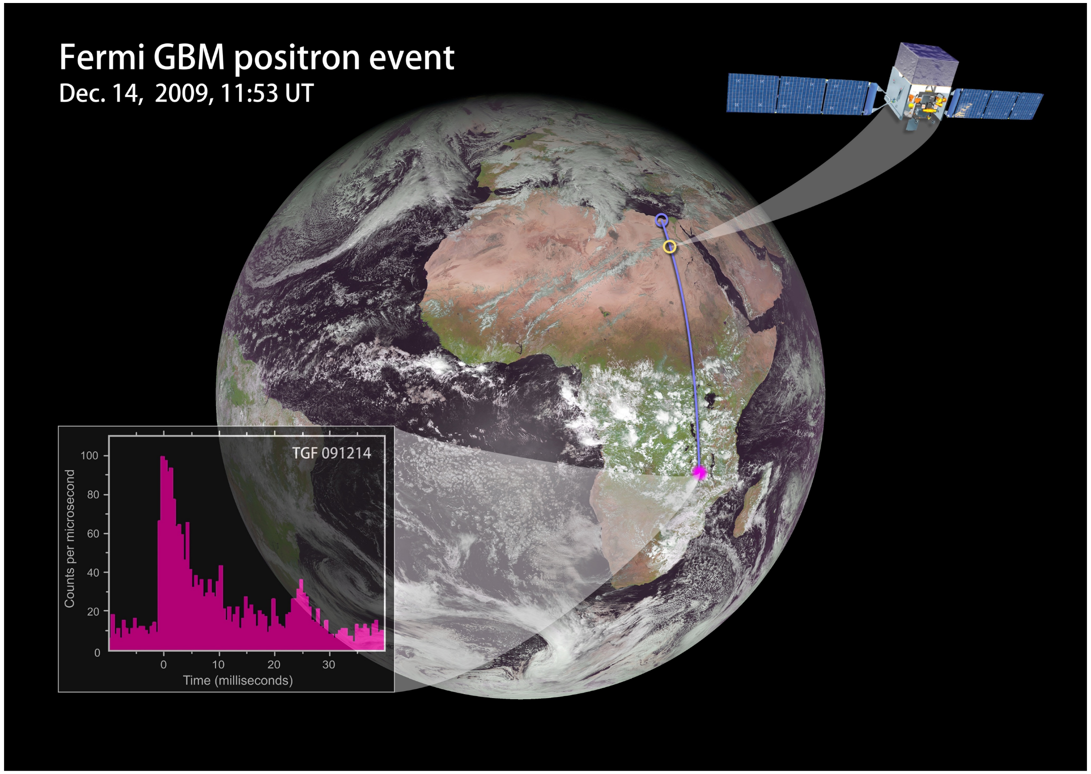


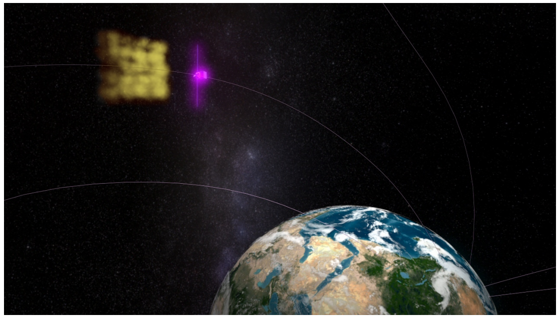
V. Bui et al., IEEE 2015 CSCI, 386–391,(2015), doi:10.1109/CSCI.2015.120.

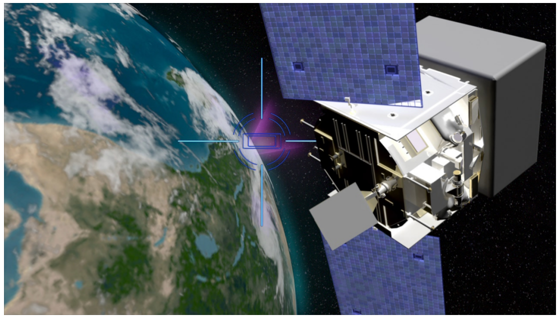
Terrestrial Electron Beams (TEBs)

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.









The Transient sky