Observation of Terrestrial Gamma-ray Flashes with Fermi LAT

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Terrestrial Gamma-Ray Flashes (TGFs) are millisecond bursts of high-energy photons, electrons, and positrons originating in Earth's atmosphere and associated with powerful thunderstorms. The Fermi Gamma ray Burst Monitor (GBM) has detected hundreds of TGFs, some with energies up to 40 MeV. Recent AGILE observations of photons up to ~100 MeV in TGFs pose a significant challenge to the relativistic runaway electron avalanche mechanism that is generally believed to be responsible for these bremsstrahlung gamma rays. With its large area, high segmentation, and low deadtime, the Fermi Large Area Telescope (LAT) is a powerful instrument for measuring the high energy emission of these short, intense transients. Here we present early results of a program of observing TGFs with the LAT.

Overview of Terrestrial Gamma-ray Flashes (TGFs)

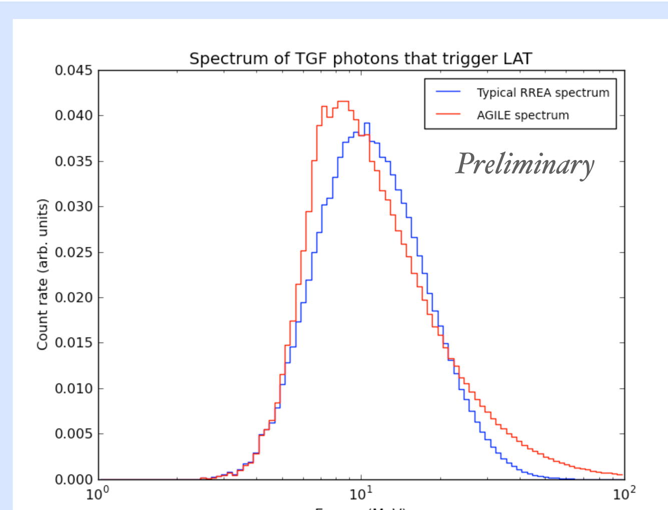
The Fermi Gamma ray Burst Monitor (GBM) detects TGFs at a rate of one every ~3.7 days (Briggs et al. 2009, Briggs et al. 2010, Connaughton et al. 2010) with its on-board burst detection algorithms. TGFs typically last 0.1-1 ms and contain photons up to ~20 MeV. A subset of these TGFs has been found to be simultaneous with lightning events to within ~40 μs. The lightning locations are typically within 300 km of the sub-satellite point. Recent observations with AGILE (Tavani et al. 2011) show a power-law spectrum of gamma rays above 10 MeV, extending to ~100 MeV, which is in significant disagreement with the prediction of the generally accepted model for the production of TGFs, the Relativistic Runaway Electron Avalanche (RREA) process. If confirmed, such high energy photons would require a new acceleration mechanism.

Observing TGFs with Fermi LAT

Although the Fermi LAT is generally pointed away from the Earth, surveying the sky, upward-going gamma rays can trigger the instrument. We have searched the LAT science data stream near the times of TGFs detected by GBM, looking for evidence of high energy photons. We find a clear excess in the LAT trigger rate and dowlinked event rate during TGFs, and we conclude that **LAT detects a large fraction of GBM-detected TGFs**. However, in sky survey attitude, the LAT is not configured optimally to accept gamma rays entering from behind the instrument. To make detailed measurements of TGFs, then, we need to reorient Fermi to put the nadir within the LAT aperture.

A nadir-observing Guest Investigation is now underway during Fermi Cycle 4. From 2011 July 26 to October 21, we have performed thirteen ~4-hour nadir pointings. Thirteen more will be scheduled before 2012 August. While the LAT is nadir-pointed, we disable the on-board event filtering to ensure that every event that causes the LAT to trigger is telemetered to the ground. **We have measured 12 TGFs so far in the nadir pointings, and analysis of these TGF events is in progress**.

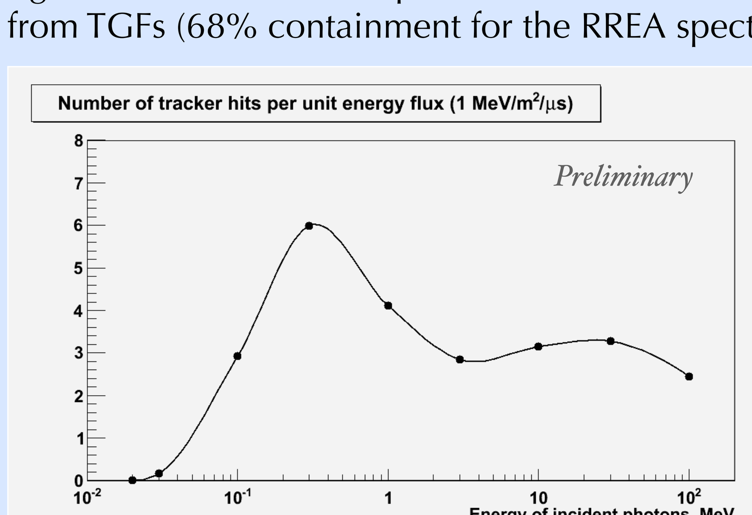
LAT response to low-energy gamma rays from TGFs



The overwhelming majority of photons in TGFs have energies below the nominal 20 MeV threshold for LAT, so it's important to understand how LAT responds to these low-energy gamma rays.

To generate a LAT trigger request, an event must hit 3 consecutive xy tracker layers (Atwood et al. 2009). The LAT trigger system then evaluates whether to read out the event, and during sky survey observations, the read out event is passed through the on-board filter, which adjudicates whether the event will be downlinked. During the nadir pointings, we disabled the on-board selection to ensure that all events that triggered LAT would be telemetered to the ground for later filtering and processing.

To understand which TGF photons cause LAT to trigger, we simulated a standard Runaway Avalanche (RREA) gamma ray spectrum and that spectrum extended with the power-law tail reported by AGILE. The figure to the above-right shows that incident photons below ~4 MeV will not cause a trigger, and that LAT triggers predominantly on photons near 10 MeV from TGFs (68% containment for the RREA spectrum is 7–17 MeV). The effective area for triggering at 10 MeV is ~2800 cm², far larger than any other instrument at this energy.



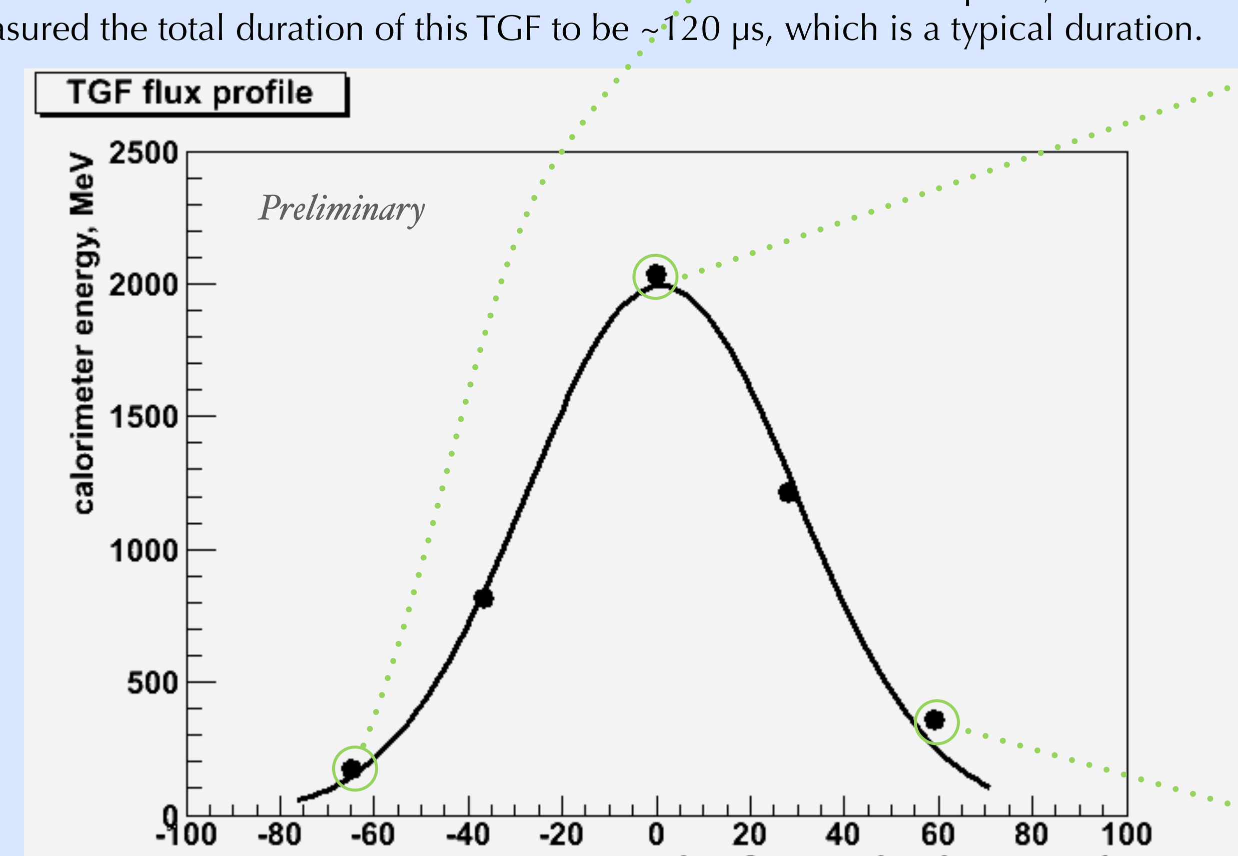
If the LAT triggers, however, the excellent low-noise performance of the detectors allows them to register photons of much lower energy. The figure below indicates that the tracker has relatively constant response to incident photons down to 0.1 MeV and below. Furthermore, the few-microsecond shaping time of the front-end electronics means that the output of the tracker represents the flux of photons above ~0.1 MeV integrated over several microseconds.

Thus, **the LAT trigger is most sensitive to photons near 10 MeV from the TGF spectrum, and when triggered, the LAT registers the fluence of photons above ~0.1 MeV in the few microseconds preceding the trigger**.

Example TGF in nadir pointing: TGF110829.562

While Fermi was nadir-pointed on 2011 Aug 29, passing over the Caribbean, the GBM and LAT independently detected a bright TGF. At this same time, a lightning event was geo-located from its VLF radio emissions within ~20 km of the Fermi sub-satellite point, so this TGF illuminated LAT nearly on axis. Both GBM and LAT measured the total duration of this TGF to be ~120 μs, which is a typical duration.

This TGF was extremely bright in LAT. The rate of trigger requests peaked above 1 MHz, suggesting that the flux of ~7–17 MeV photons peaked above 400 ph cm^{-2} s^{-1}. The LAT triggered and read out five times during the TGF. **Each read out event is complex: each has high photon multiplicity, i.e. is composed of many incident photons rather than a single photon**. As indicated in the inset figure, the energy deposited in the calorimeter spans ~150 MeV to ~2 GeV per ~5 μs integration time (i.e. per trigger). The calorimeter energy and time of each trigger is shown as a solid circle, and the solid curve is a best-fit gaussian profile, indicating that the flash lightcurve can be described as a simple, symmetric shape.



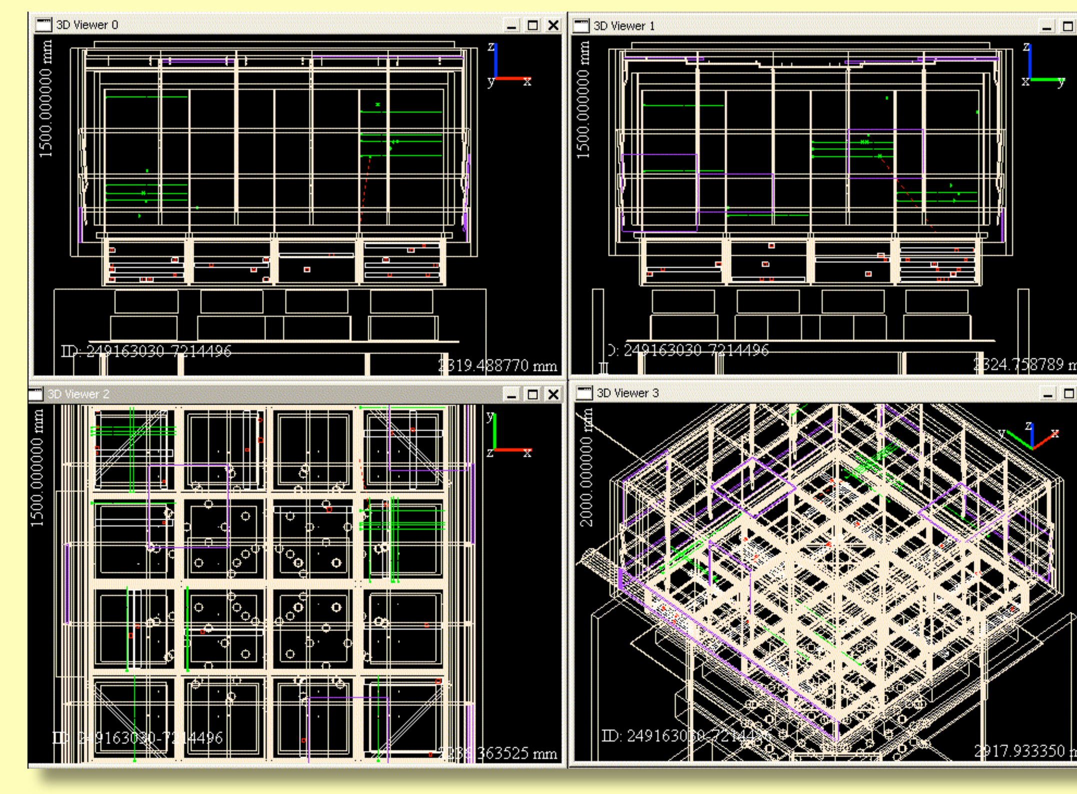
"Event displays" for three of the five triggers are shown in the yellow boxes to the right. Arrows indicate which trigger is displayed in each box.

Reconstructing individual photons among the many arriving within the integration time is quite challenging; however **we can address** scientifically interesting questions of (1) the **energy fluence during in the ~5 μs integration time** in each readout, (2) the **average rate of photons above ~4 MeV** between each readout, and (3) the **energy endpoint of the TGF spectrum**.

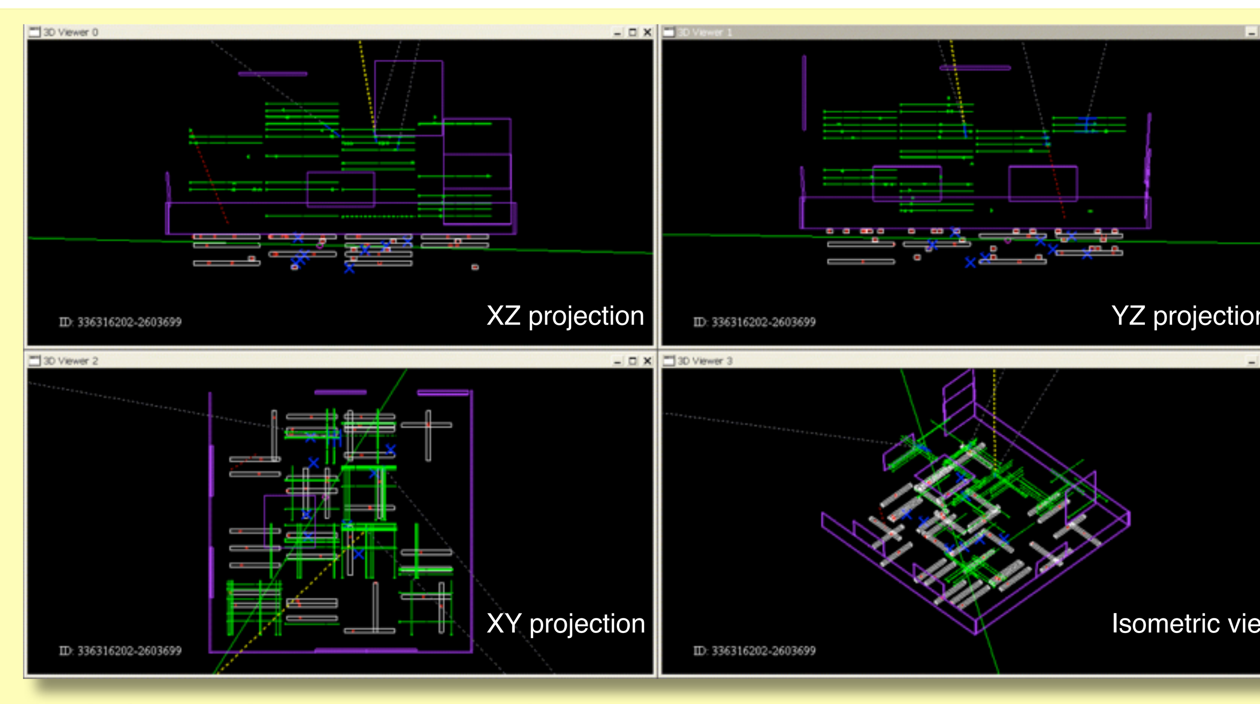
Status and conclusions

The Fermi LAT clearly detects Terrestrial Gamma ray Flashes.

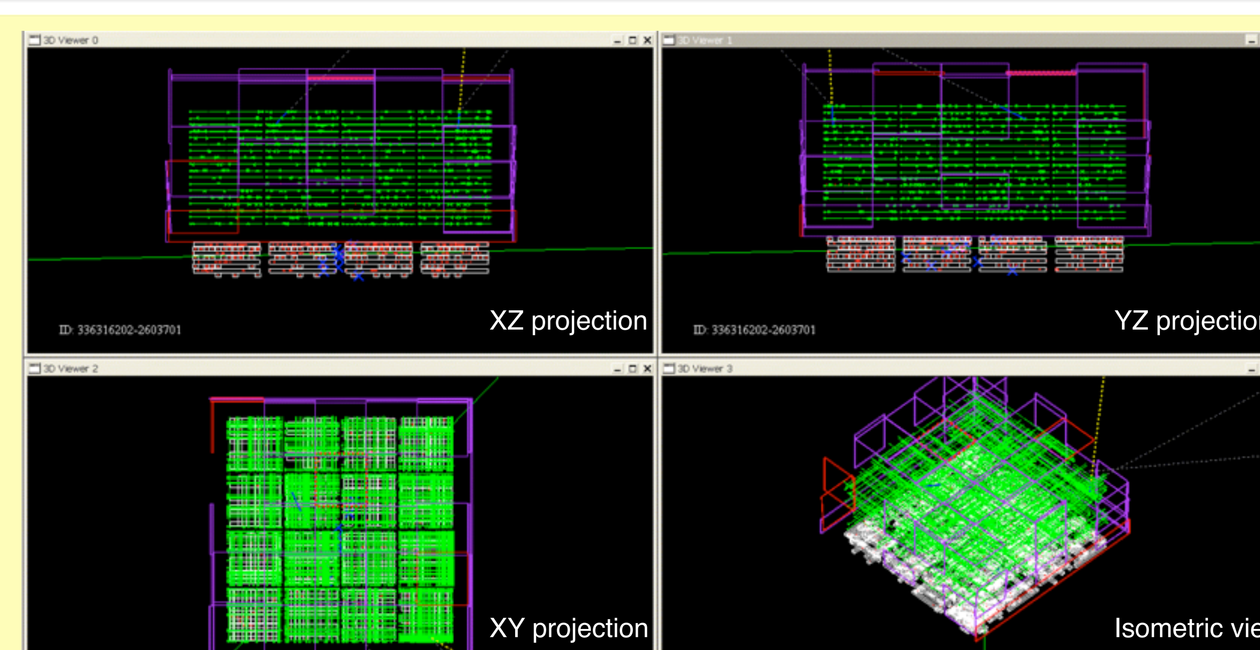
- In sky survey attitude, LAT detects a subset of the TGFs detected by Fermi GBM. They are apparent as excess trigger requests and downlinked events above the average background rates at the times of TGFs.
- In a special instrument configuration optimized for TGF measurement and pointed at the nadir, LAT has detected 12 TGFs.
- TGFs are extraordinarily bright, with fluxes peaking above 2500 ph cm^{-2} s^{-1}. The detected events are clearly dominated by multiple low energy gamma rays in coincidence within the few-microsecond shaping time of the LAT detector electronics.
- We cannot yet evaluate whether the spectrum above 20 MeV deviates from the prediction of the RREA model. Careful analysis is required to distinguish individual >50 MeV photons among multiple 5-10 MeV photons within the detector integration time. This analysis is on-going.



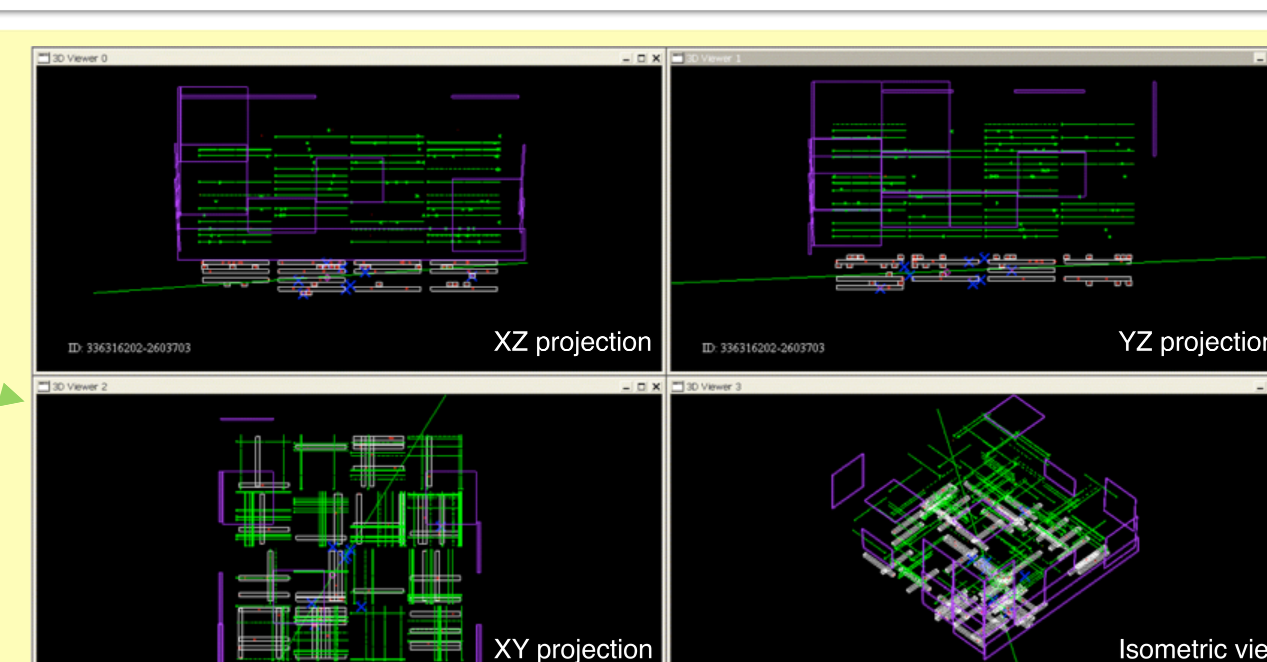
LAT Event Display. Each contains four views: the upper panels are XZ and YZ projections; the lower left panel is an XY projection; and the lower right panel is an isometric view. The Z direction is the LAT boresight, and the TKR and CAL towers are arrayed in the XY plane. Individual ACD tiles, TKR towers, CAL towers, electronics boxes, and major structural components are indicated by white outlines in the first event display. For clarity in the figures below, we have suppressed those fiducial outlines and left only the indicators of measured energy deposition: purple outlines for ACD tiles, green lines and crosses for TKR strips, and white outlines with red squares for CAL crystals.



At 65 us before peak, LAT sees ~40 photons in ~5 μs integration time, assuming typical RREA spectrum. Total energy deposited in calorimeter = 165 MeV, distributed among ~40 photons.



Near peak of TGF, LAT sees ~500 photons in ~5 μs integration time, assuming typical RREA spectrum. Total energy deposited in calorimeter = 2030 MeV, distributed among ~500 photons.



At 60 us after peak, LAT sees ~90 photons in ~5 μs integration time, assuming typical RREA spectrum. Total energy deposited in calorimeter = 350 MeV, distributed among ~90 photons.

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References
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