PROCEEDINGS OF SCIENCE

Fermi GBM observations of Terrestrial Gamma Flashes

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For the GBM TGF Team

Terrestrial Gamma-ray Flashes (TGFs) are brief pulses of energetic radiation associated with thunderstorms and lightning. Observations of TGFs by the *Fermi* Gamma-ray Burst Monitor (GBM) have yielded rich science and new discoveries. Studies of TGF pulse morphologies reveal that they can be either symmetrical or faster in their rise than their decay, and can occur singly or in multiple, sometimes overlapping, pulses. Correlations of GBM-detected TGFs with ground-based radio observations of lightning discharges made by the World Wide Lightning Location Network show that the discharges and the TGFs are simultaneous to $\sim 40\mu$s, with the discharge typically occurring within 300 km of the sub-spacecraft point. Rare TGFs are detected via an electron beam produced in a storm near one of the termini of the magnetic field line crossing *Fermi*. Bright electron TGFs show a prominent 511 keV annihilation line in their energy spectra, showing that this beam contains not only electrons, but also positrons, with a positron fraction between 10 and 20%.

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1. Observations

Terrestrial Gamma-ray Flashes (TGFs) were discovered in the early 1990s with the Burst and Transient Source Experiment (BATSE) on the Compton Gamma-Ray Observatory. They have since been observed from space with the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [11, 6], Astro-rivelatore Gamma a Immagini LEggero (AGILE) [8] and now with the Gamma-ray Burst Monitor (GBM) on the *Fermi* Space Telescope [2, 3, 5]. The measured radiation is believed to consist of bremsstrahlung photons emitted by energetic electrons, with the energetic electrons originating from acceleration by strong electric fields associated with thunderstorms. The accelerated electrons develop into an upward cascade of energetic electrons, positrons and photons in a process known as Relativistic Runaway Electron Avalanche (RREA) [7, 4]. The precise site of the strong electric field and the mechanism that initiates TGFs are less well understood.

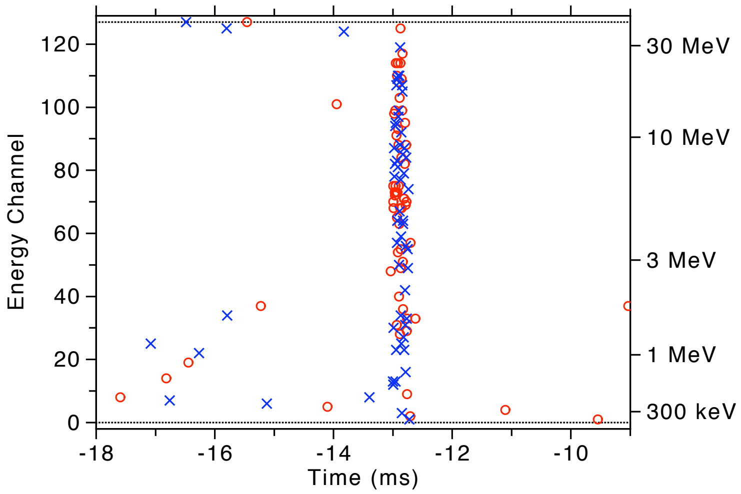

Figure 1: This plot of GBM TGF 081001.392 shows individual counts recorded in the two GBM BGO detectors: red circles for BGO 0 and blue crosses for BGO 1. In most cases a count is a photon from the TGF, recording approximately the incident energy. Some of the counts are background photons or particles. The TGF is seen to last only a small fraction of a millisecond and to have photons with energies to ≈30 MeV.

GBM consists of fourteen scintillation detectors of two types arranged to view the unocculted sky [9]. Twelve NaI detectors cover the energy range 8 keV to 1 MeV, while two BGO detectors cover the energy range 200 keV to 40 MeV. The high density of BGO and the high atomic number of Bi give BGO an excellent response to gamma-rays. The 14 kg GBM BGO detectors have a high probability of absorbing the full energy of incident gamma-rays to ∼10 MeV and are superb detectors for TGFs. A typical TGF is shorter and more energetic than the Gamma-Ray Bursts (GRBs) for which GBM was designed to observe, but the shortest GBM on-board triggering time-scale of 16 ms is still capable of detecting the brighter segment of the TGF population. Figure 1 shows the individual photon arrival times of a typical GBM TGF in the 16 ms triggering window, with the vertical scale representing their energies. In this case, the highest measured energy is ≈30 MeV. By contrast, because RHESSI is able to downlink all of its event data, it sees many more and weaker TGFs than can trigger GBM. The nearly 1000 TGFs detected by RHESSI make clear

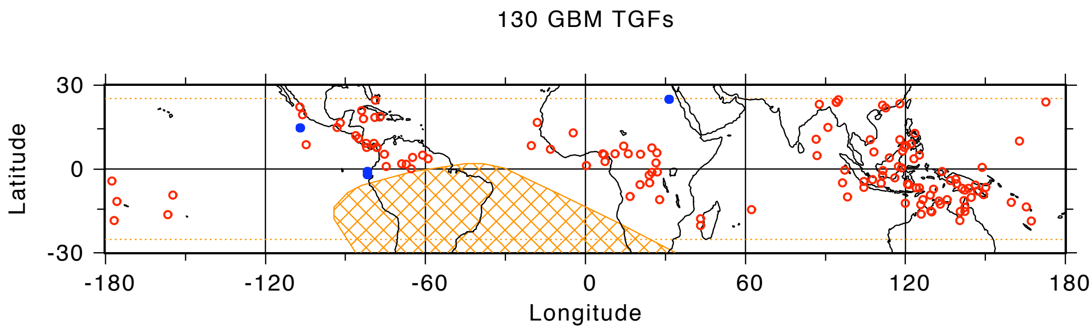

Figure 2: Locations of *Fermi* at the times of the first 130 TGFs detected in orbit by GBM. Red circles are for gamma-ray TGFs; Blue circles are for electron TGFs. The orange cross-hatches designate the South Atlantic Anomaly, a region of heightened trapped radiation in which the GBM detectors are turned off and therefore TGFs cannot be detected.

the pattern suggested by BATSE of TGF detections occurring when the spacecraft nadir was close to areas of thunderstorm and lightning activity. GBM has triggered on 130 TGFs and the sub-spacecraft positions in Figure 2 show the hot spots for TGF detection. Recently, GBM has entered a mode of operation where it, too, downlinks all of its event data for selected portions of the *Fermi* orbit that are chosen according to seasonal thunderstorm activity, making it possible to search on the ground for TGFs that are too weak to trigger on the 16 ms time-scale.

2. Temporal Properties

TGF pulses can be fit either by a Gaussian or a LogNormal function. In some TGFs, the pulses appear to overlap, determined by eye, but also by a statistcal preference for two rather than one functions in their fit. Individual TGF pulses are generally a few hundred μs in duration, with T_{50} between 50 and 200 μs [5], T_{50} being defined as the period containing 50% of the total pulse fluence. There are exceptions. Most TGF pulses longer than a ms appear to form a separate class of events that are characterized by a softer spectrum in addition to a longer duration. These long, soft TGFs are actually electrons. As expected in the RREA process, large numbers of electrons are generated as secondaries through Compton scattering and pair production. These electrons are captured on magnetic field lines, with a distribution of pitch angles relative to the field line direction. If the field line on which they travel crosses *Fermi*, some of these electrons will be detected by GBM, with a spread in arrival times that reflects the distribution of pitch angles. In one case, two such pulses were observed, with the second pulse produced by electrons that missed *Fermi*, travelled towards the magnetic footprint, and magnetically mirrored at an atmospheric height that allowed them to escape without absorption and travel back to *Fermi*.

3. Correlations with lightning

The association between TGFs and thunderstorms has long been known. GPS-timing on-board *Fermi* and $\approx 3\mu$s absolute timing of GBM allow correlations between GBM-detected TGFs and the radio signals of lightning discharges to be established with unprecedented accuracy. Using the

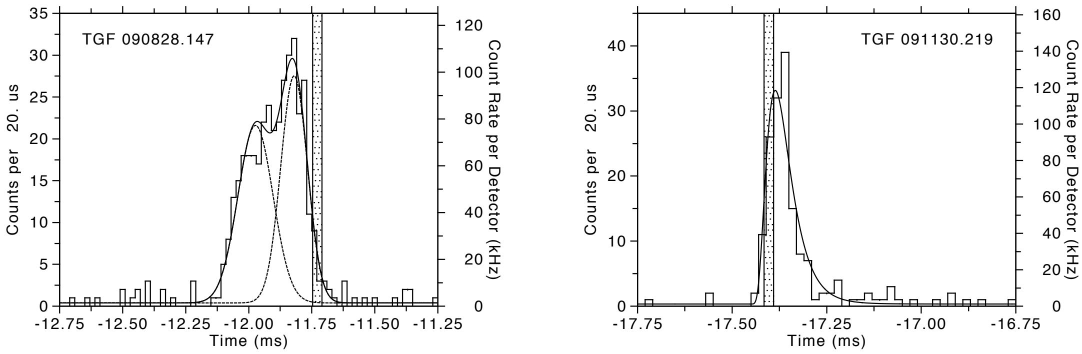

Figure 3: Timing comparison between two GBM TGFs and their associated WWLLN-detected sferics. The pairs of vertical lines filled with dots indicate the times of the sferics, with the separations of the lines indicating the timing uncertainty. While the TGFs and lightning sferics are closely coupled in time, there is no set time order. For TGF 090828.147, the sferic occurs after both pulses of the TGF, while for TGF 091130.219 the sferic is at or before the peak of the gamma-ray pulse. From [3].

World Wide Lightning Location Network which can locate individual discharges to 20 km and 30 μs [10], we find closely associated electrical discharges for 30% of GBM-detected TGFs. These matches are statistically significant: using controls, the probabilities of chance associations are shown to range from <0.1% to 0.7%. Using the TGFs with associated sferics, the peak times of lightning and TGFs are found to be simultaneous to within ≈40 μs [2, 3], which represents a nearly two orders of magnitude tighter simultaneity than previously demonstrated. The near simultaneity between TGFs and lightning suggests that lightning discharges directly initiate the TGFs.

Superposing the times of the peak electrical discharge current measured by the WWLLN on the GBM TGF lightcurves as in Figure 3 shows that the discharge can occur before, during, or after the peak gamma-ray emission, but usually occurs during a TGF pulse. There are two exceptions out of the 15 matches, where the discharge occurs several ms before or after (one of each) the TGF.

All 15 TGFs with associated lightning discharges were detected when *Fermi* was within 300 km of the source of the lightning (Fig. 4). For the remaining TGFs in this sample that do not have an individual associated discharge, lightning activity occurs within 300 km of the spacecraft nadir in a 10 minute window centered on the TGF trigger time in all but a few exceptions. The exceptions are the long events mentioned above, where we are detecting not the gamma-ray signal from the TGF, but the electrons which were carried to *Fermi* from a storm at the magnetic footprint. This hypothesis is confirmed by the presence of storms at one of the magnetic termini for three of the four long TGFs. The remaining TGF was detected when *Fermi* was over Africa, shows no storm either at the nadir or the footprints, and is probably an electron event with the poorer coverage of the WWLLN for Africa explaining the lack of lightning at the footprint.

4. Positron beams into space

Having established the long TGFs are electrons traveling on magnetic field lines from distant storms, we now turn to their spectra. Figure 5 shows the energy spectrum from the first electron

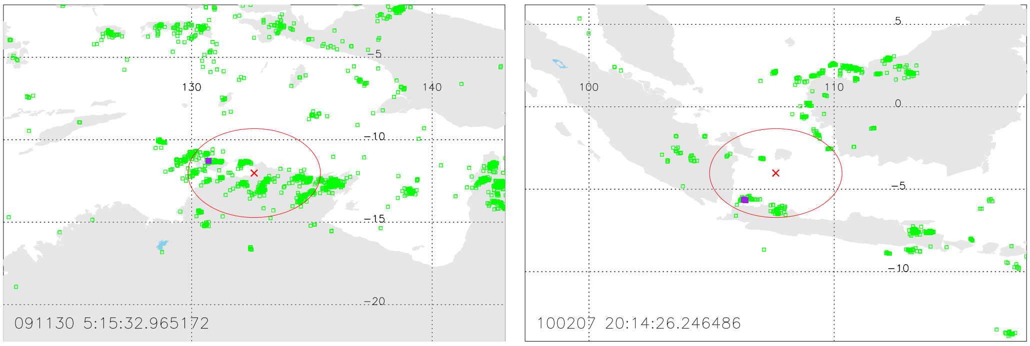

Figure 4: Lightning locations detected with WWLLN near the sub-*Fermi* points for GBM TGFs 091130.219 and 100207.843. The sub-*Fermi* position is indicated with a red-cross in the center of each map; about this is a 300 km radius circle. Each lightning discharge within ± 10 minutes is shown with a green, open square. The specific discharge temporally associated with the TGF is shown with a purple, solid square. From [3].

TGF detected by GBM. An empirical model of an exponential shape, $A\exp{-E/E_0}$, matches the data well when the E-folding energy E_0 is optimized. The model requires the addition of a line at 511 keV that indicates the presence of positrons which annihilate upon hitting *Fermi*. This feature is seen in all three of the bright electron TGFs, with a positron fraction, implied by the line strength, of 10 - 20% [1].

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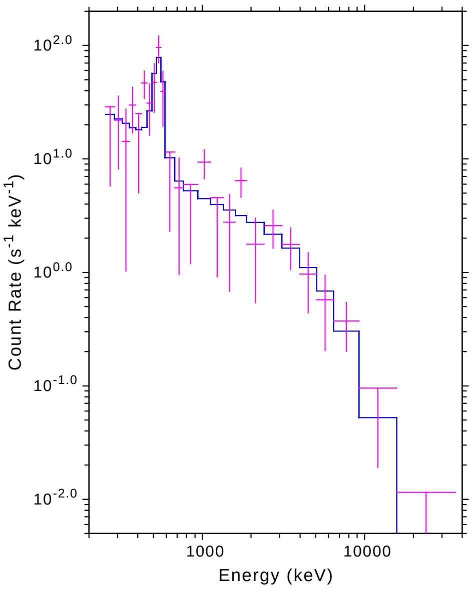

Figure 5: Spectral data (magenta points) and model fits (blue histograms) for TGF 080807. Data points within 1σ of zero are displayed as 2σ upper-limits (T-symbols). The models are the best-fit mixtures of electrons and positrons converted into expected counts in BGO detector 0 with GRESS simulations. From [1].

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