

TETRA observation of gamma-rays at ground level associated with nearby thunderstorms

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[1] Terrestrial gamma-ray flashes (TGFs)—very short, intense bursts of electrons, positrons, and energetic photons originating from terrestrial thunderstorms—have been detected with satellite instruments. TGF and Energetic Thunderstorm Rooftop Array (TETRA), an array of NaI(Tl) scintillators at Louisiana State University, has now been used to detect similar bursts of 50 keV to over 2 MeV gamma-rays at ground level. After 2.6 years of observation, 24 events with durations 0.02–4.2 ms have been detected associated with nearby lightning, three of them coincident events observed by detectors separated by ~1000 m. Nine of the events occurred within 6 ms and 5 km of negative polarity cloud-to-ground lightning strokes with measured currents in excess of 20 kA. The events reported here constitute the first catalog of TGFs observed at ground level in close proximity to the acceleration site.

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1. Introduction

[2] Lightning provides the most powerful natural accelerator available on Earth for producing high-energy particles. Intense millisecond-scale bursts of gamma-rays produced by upward moving electrons accelerated to energies of tens of MeV or more have been detected with satellite instruments. These terrestrial gamma flashes (TGFs) have been shown to be associated mainly with positive polarity intracloud lightning, with the particle acceleration occurring at altitudes of 10–15 km. We show here that negative polarity cloud-to-ground lightning accelerates particles downward and produces gamma-rays with energies of at least 2 MeV. We present a sample of 24 TGFs detected at ground level associated with nearby (< 5 km) lightning observed over approximately 2.6 years mainly during spring and summer thunderstorms in Louisiana.

[3] TGFs were first observed by the Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma-Ray Observatory [Fishman et al., 1994; Gjesteland et al., 2012] and have now been observed by five additional

satellite detectors—the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [Smith et al., 2005; Grefenstette et al., 2009], the Gamma-Ray Imaging Detector [Marisaldi et al., 2010] and Minicalorimeter [Marisaldi et al., 2011; Tavani et al., 2011] on Astro-rivelatore Gamma a Immagini Leggero (AGILE), and the Gamma-ray Burst Monitor (GBM) [Cohen et al., 2010; Fishman et al., 2011; Briggs et al., 2013] and Large Area Telescope [Grove et al., 2012] on the Fermi mission. Events are typically detected close to the subsatellite point [Grefenstette et al., 2009] and are correlated both with regions of high thunderstorm activity [Cohen et al., 2006; Fuschino et al., 2011; Marisaldi et al., 2011] and with individual positive polarity intracloud (+IC) and possibly positive cloud-to-ground (+CG) lightning discharges to within 1–2 ms [Inan et al., 2006; Stanley et al., 2006; Hazelton et al., 2009]. (Positive polarity is needed to produce the upward beam of electrons and secondary photons necessary for detection of TGFs from space [Dwyer, 2003; Cohen et al., 2010].) Lightning flashes are known to emit a large fraction of their electromagnetic energy into low-frequency (0.3–30 kHz) atmospheric radio signals (sferics), which can be located accurately by arrival time measurements in a worldwide radio receiver network [Rodger et al., 2009]. TGFs are well correlated both with sferics [Inan et al., 2006; Connaughton et al., 2013] and the Lightning Imaging Sensor-Optical Transient Detector and World Wide Lightning Location Network (WWLLN) high-resolution lightning data [Hazelton et al., 2009; Smith et al., 2010; Fuschino et al., 2011].

[4] GBM has also demonstrated that in some cases, as the original gammas propagate upward through the atmosphere, they produce secondary e^\pm via pair production [Cohen et al., 2010; Briggs et al., 2011] that escape into space. These secondaries are then able to spiral around magnetic field lines to the spacecraft far from the lightning location,

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producing Terrestrial Electron Beams characterized by 511 keV signals and both long-duration pulses and delayed pulses resulting from particles moving past the spacecraft and then reflecting from magnetic mirror points and returning to be detected by GBM.

[5] Given the altitude of the satellites around 500 km, the observations point to beaming of the photons upward with a $\sim 30^\circ$ half-angle cone coupled with attenuation of wide-angle photons passing through greater atmospheric path lengths [Grefenstette *et al.*, 2008; Østgaard *et al.*, 2008; Hazelton *et al.*, 2009; Gjesteland *et al.*, 2011]. Based on the spectra observed by RHESSI [Smith *et al.*, 2005], Dwyer and Smith [2005] performed detailed Monte Carlo simulations showing that the spectra were consistent with bremsstrahlung from electrons accelerated by the relativistic runaway electron avalanche (RREA) mechanism [Gurevich *et al.*, 1992; Dwyer, 2003] at altitudes near thunderstorm tops. Over the 0.1–10 MeV range, the spectrum observed by AGILE [Marisaldi *et al.*, 2011] has been well fit by a cut-off power law of the form $F(E) \sim E^{-\alpha} e^{-E/E_0}$ with E_0 compatible with the ~ 7 MeV electron energies predicted by RREA, but the observation of individual gamma-rays with energies in excess of 40 MeV has posed a challenge for the emission models [Tavani *et al.*, 2011; Celestin *et al.*, 2012].

[6] RREA models of TGFS in the atmosphere [Dwyer, 2003, 2008; Gjesteland *et al.*, 2011] start with MeV seed electrons accelerated when lightning-associated electric fields overcome local energy losses. These accelerated electrons produce photons, secondary electrons, positrons, and X-rays by bremsstrahlung, pair creation, and Compton scattering. The avalanche may be further seeded by the relativistic feedback mechanism, in which backward propagating positrons and X-rays lengthen the TGF durations up to several milliseconds as seen in satellite observations [Dwyer, 2008; Dwyer *et al.*, 2012a and references therein]. Ground-based lightning observations and comparisons of model calculations with the measured spectra indicate that the TGFS are produced at altitudes ~ 10 –25 km [Dwyer and Smith, 2005; Grefenstette *et al.*, 2008; Shao *et al.*, 2010; Gjesteland *et al.*, 2010; Cummer *et al.*, 2011; Xu *et al.*, 2012]. A more detailed review of TGF models and observations is presented by Dwyer *et al.* [2012b].

[7] TGF observations from satellite platforms are limited to events apparently beamed upward and large enough to be detected even in the presence of attenuation and Compton scattering by the atmosphere. Although these events observed from space are extremely intense (gamma-ray rates in excess of 300 kHz measured with BATSE), the bulk of the events are presumably smaller events which can only be observed much closer to the lightning—i.e., at aircraft or balloon altitude or at ground level [Smith *et al.*, 2011; Briggs *et al.*, 2013; Gjesteland *et al.*, 2012; Østgaard *et al.*, 2012]. [Dwyer, 2012] has suggested a possible downward directed positron and gamma-ray signature from TGFS. Observations at ground level are necessary to observe the downward component, to better understand the TGF intensity distribution and emission pattern, to understand whether the observed 30° beaming is intrinsic to the emission process or is the result of atmospheric attenuation, and to measure the spectrum versus altitude relationship. As a practical consideration, it has been suggested that lightning-induced gamma-rays might produce a significant radiation exposure for airplane passengers flying close to a lightning stroke [Dwyer *et al.*, 2010].

[8] The majority of ground-level observation projects currently focus on correlating satellite-observed TGFS with lightning and measuring possible associated magnetic signatures [Cummer *et al.*, 2011; Lu *et al.*, 2011]. The International Center for Lightning Research and Testing (ICLRT) project, however, has reported two gamma-ray bursts, one in association with triggered lightning of negative polarity [Dwyer *et al.*, 2004] and another in association with nearby negative polarity cloud-to-ground (–CG) lightning [Dwyer *et al.*, 2012b]. TGFS associated with negative polarity lightning strikes, as with these ICLRT events, produce downward beams of photons which can be detected from the ground. ICLRT operates in a triggered mode, requiring either a triggered lightning current above 6 kA or the simultaneous trigger of two optical sensors.

[9] The array of particle detectors at Aragats Space Environment Center has detected thunderstorm-associated ground enhancements above 7 MeV with timescales of microseconds and tens of minutes [Chilingarian *et al.*, 2010, 2011]. These have been detected approximately once per year and seem to be correlated with –IC lightning.

[10] In addition, a mountaintop detector has observed 3 ms bursts of X-rays associated with CG lightning [Moore *et al.*, 2001]. Longer duration (40 s to minutes or longer) X-ray and gamma-ray events have been reported previously from the ground [Tsuchiya *et al.*, 2011, 2013], but the only other case in which a TGF-like event with millisecond emission of MeV gammas has been observed from within the atmosphere is the observation by the Airborne Detector for Energetic Lightning Emissions aboard an aircraft at an altitude of 14 km [Smith *et al.*, 2011]. Here we present observations from July 2010 through February 2013 of 24 TGF-like events in which 50 keV–2 MeV gamma-rays are observed at ground level in shorter than 5 ms bursts associated with nearby negative polarity lightning.

2. Detector Description

[11] The TGF and Energetic Thunderstorm Rooftop Array (TETRA) consists of an array of twelve $19 \text{ cm} \times 19 \text{ cm} \times 5 \text{ mm}$ NaI(Tl) scintillators designed to detect the gamma-ray emissions from nearby lightning flashes over the range 50 keV–2 MeV. The scintillators are mounted in four detector boxes, each containing three NaI detectors viewed by individual photomultiplier tubes (PMTs). The boxes are spaced at the corners of a $\sim 700 \times 1300 \text{ m}^2$ area on four high rooftops at the Baton Rouge campus of Louisiana State University (LSU) at latitude 30.41° and longitude -91.18° . Unlike ICLRT, TETRA operates in a self-triggered mode, allowing for events to be recorded without requiring the direct detection of lightning.

[12] Each TETRA detector box contains three NaI scintillator plates oriented at 30° from the zenith direction and separated by 120° in azimuth. Each NaI(Tl) crystal is hermetically sealed between a 6.4 mm thick glass optical window on one flat face and a 0.75 mm thick aluminum entrance window on the other face. An ultraviolet transmitting Lucite light guide is coupled to the glass window, and the light is viewed by an Electron Tubes 9390KB 130 mm photomultiplier tube with a standard bi-alkali photocathode. The scintillator-PMT assemblies are housed in $\sim 2.5 \text{ cm}$ thick plastic foam insulation to prevent rapid temperature changes. Electronics boards in each detector box supply high voltage, amplify and shape

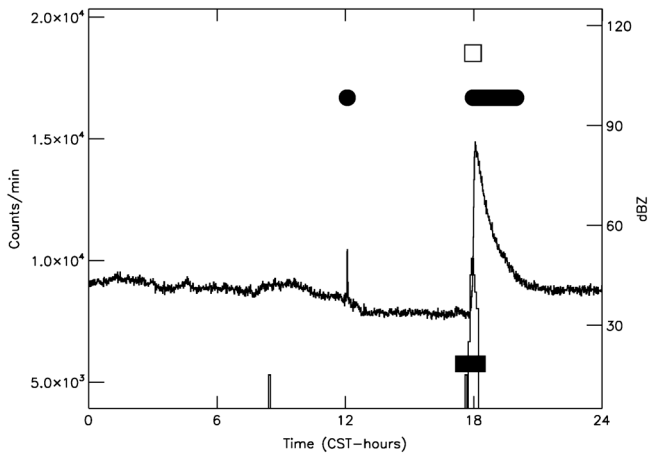


Figure 1. Summed NaI counting rate per minute in Box 3 on 18 August 2011 (heavy black line, left-hand scale). Thin black histogram near the bottom (right-hand scale) shows radar reflectivity. The filled rectangle at the bottom marks times of lightning strikes within 8 km. The row of filled circles near the top marks intervals in which the count rate in 60 s bins exceeds the day’s average by 3σ ; the open square marks the TETRA trigger, i.e., the interval when the rate in 2 ms bins exceeds the day’s average by 20σ .

the PMT outputs, provide an internal trigger for the data acquisition software, digitize the data, assign timestamps, and record ADC values for each event. Once triggered, each PMT anode output is integrated and assigned a 12 bit analog-to-digital converter (ADC) value. A 32 channel ADC board, a Lissan iQ GPS board, and a Mesa field-programmable gate array (FPGA) board are incorporated onto a PC104 stack controlled by a Microcomputer Systems VDX-6357 800 MHz 486 CPU board running a QNX operating system. The FPGA is programmed to handle trigger logic, clock functionality, and event time stamping. We refer to the Mesa board together with its FPGA as the trigger logic module. Each is capable of detecting events at a sustained rate of 30 kHz and a burst rate of up to 70 kHz. The data are then transferred over a wireless link to a central station for analysis. The initial version of the data acquisition software, used from October 2010 to January 2013, utilized a network time protocol to keep timestamps accurate to within approximately 2 ms and to monitor the absolute timing uncertainty. The current version of the software, implemented in January 2013, uses a GPS-disciplined clock to produce timestamps accurate to within 200 ns.

[13] The ADC-to-energy conversion is calibrated with radioactive sources (^{22}Na , ^{137}Cs , and ^{60}Co). Individual detector energy resolution ranges from 9 to 13.5% full width at half maximum (FWHM) at 662 keV and from 5.5 to 10.8% at 1.3 MeV. The total interaction probability in the NaI scintillators is 95% at 100 keV, 82% at 500 keV, and 10% at 1 MeV (with photoelectric interaction probabilities 93%, 26%, and 0.63%, respectively). In addition to the three NaI scintillators, one detector box contains a 2.5 cm diameter by 2.5 cm thick cerium-doped lanthanum bromide ($\text{LaBr}_3\text{:Ce}$) scintillator that provides high-energy-resolution measurements (3.5% FWHM at 662 keV) of intense events. Beginning in October 2012, all boxes contain a bare PMT to check for electronic noise.

[14] Data are accumulated for a day at a time for each of the four detector boxes individually. The daily analysis software selects events with signals corresponding to at least 50 keV deposited energy within $1\mu\text{s}$. The data are then binned into 2 ms bins and assigned a timestamp. TETRA triggers are selected with counts/2 ms at least 20 standard deviations above the mean for the day. Once days with excessive electronic noise or other instrumental problems are removed, there are 835.09 days of live time and 1303 TETRA triggers.

3. Results

[15] In Figure 1, the heavy black line shows a time history of the count rates for the three NaI photomultiplier tubes of $>50\text{keV}$ events in a single detector box for 1 day. The total count rate, plotted in counts per minute, is reasonably constant for the first 17 h and then increases by a factor of approximately 2 beginning at about 1800 CST. The small peak in the count rate seen at about 1200 CST is due to noise in the system seen only in a single PMT on a 60 s timescale. The thin black histogram near the bottom shows the local radar reflectivity in decibels acquired from www.wunderground.com, indicating rain, thunderstorms, hail, or strong winds. The increase in the NaI detector rate is clearly correlated with rainstorms. The gamma-ray spectrum, measured during a rain event with the high-resolution $\text{LaBr}_3\text{:Ce}$ detector mounted together with the NaI detectors in one of the detector boxes, shows a clear indication of 295, 352, 609, 1120, and 1764 keV Bi^{214} and Pb^{214} lines characteristic of radon decay (Figure 2).

[16] The filled rectangle near the bottom of Figure 1 at approximately 1800 CST marks the times of lightning strikes detected by the U.S. Precision Lightning Network (USPLN) Unidata Program within 8 km of the LSU campus. These are mainly cloud-to-ground events with positions accurate to approximately 0.4 – 0.8 km. In the upper section of the diagram, the line of filled circles marks 60 s intervals in which

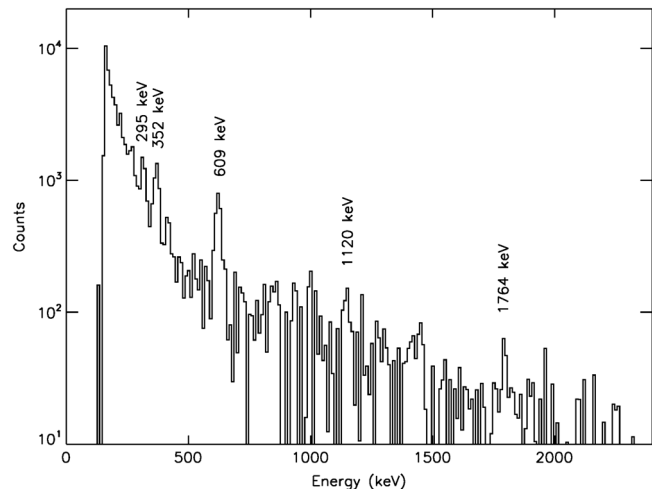


Figure 2. $\text{LaBr}_3\text{:Ce}$ rain spectrum. $\text{LaBr}_3\text{:Ce}$ background-subtracted spectrum during a 6 h precipitation event showing radon lines at 295 keV, 352 keV, 609 keV, 1120 keV, and 1764 keV.

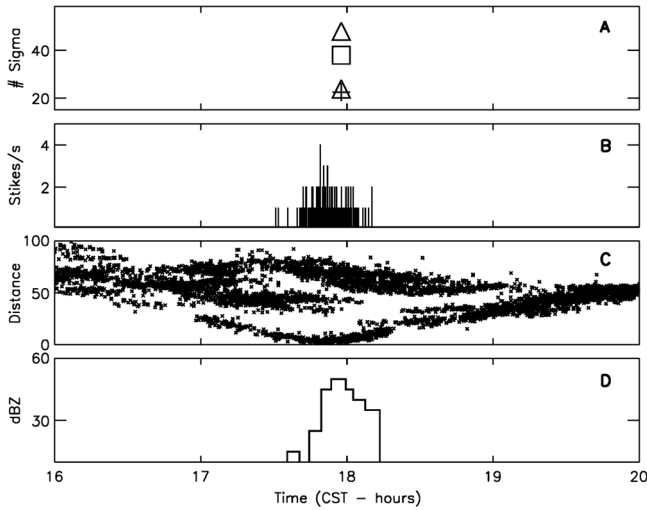


Figure 3. TETRA report for 18 August 2011 events. (a) Triggers detected on 18 August 2011 (NaI signals above 50 keV in a single detector box with count rate per 2 ms in excess of 20σ above the 18 August 2011 daily mean counting rate). Box 1 triggers are indicated by plus signs, Box 3 by triangles, and Box 4 by squares. (b) Rate per second of USPLN lightning strikes within 8 km (c) Distance to each recorded lightning strike within 160 km (d) Overhead cloud density.

the NaI detector count rate is 3 standard deviations higher than the average rate for the day; these are correlated with the peak of the extended rise at the time of the rainstorms. TETRA triggers are defined as intervals during which the rate in a 2 ms window exceeds the day's average by 20σ . The TETRA trigger observed is indicated near the top of the plot as an open square. (For a typical average counting rate of 8900 min^{-1} in a detector box above 50 keV, a 20σ excess corresponds to 10 counts in the three PMTs in a detector box within a 2 ms window.)

[17] Figure 3 shows an expanded view of the data on the same day, illustrating the correlation of the triggers in individual boxes with lightning and cloud density overhead. Figure 3a shows the times of the triggers in each detector box. Figure 3b shows the rate per second of lightning strikes within 8 km of the detectors, and Figure 3c shows the distance of all lightning strikes recorded by the USPLN network within 160 km. Figure 3d shows the overhead cloud density.

[18] From July 2010 through February 2013, TETRA has recorded a total of 24 events with triggers occurring within several minutes of thunderstorm activity producing at least one lightning flash within 8 km of the detectors. Such events are classified as event candidates (ECs) and are listed in Table 1. In this table each event trigger time is listed, along with the number of lightning flashes detected within ± 2.5 min and 8 km and the cloud density above TETRA. Also listed for each EC is the time difference to the lightning stroke closest in time to the event trigger, the distance to that lightning stroke, the current, the number of gamma-rays detected in the EC, and the T_{90} duration of the event (i.e., the time over which a burst emits from 5% to 95% of its total measured counts in a single detector box). The number of sigma above the mean is listed in the second to last column for each event. (For the first three events in the table, observed simultaneously in multiple detector boxes, the

smallest number of sigma above the mean is listed. These coincident events, labeled coincident event candidates—CECs—are discussed in more detail below.)

[19] TETRA's events, with an average of 20 ± 2 photons detected, are significantly smaller than the typical events observed in space. For TETRA's events, the T_{90} duration was calculated by considering all events detected within a ± 3 ms window around the trigger time, discarding the first and last 5% of timestamps for each event, and recording the time difference between the first and last events remaining. The uncertainty in the T_{90} determination is approximately $\pm 200 \mu\text{s}$ based on Monte Carlo simulations of the data.

[20] In each of the 24 events, 7 to 45 γ -rays were detected within a time window of less than 5 ms, with the total energy deposited per event ranging from 2 to 32 MeV. The distances to the nearest lightning flashes were 0.6–4.7 km. For 14 events, absolute timing was available with ~ 2 ms accuracy. For each of these 14 events, lightning was observed within 7 s of the trigger time. Nine of these events were associated with $-CG$ lightning detected within 6 ms of the trigger. Another 10 ECs were detected during June–July 2012 during a period when accurate trigger-lightning time differences were not recorded due to network timing difficulties. Eight of the ECs during that period were correlated with two intense thunderstorms that passed directly over TETRA on 6 June 2012.

[21] The accidental rate of triggers coincident within 7 s of a lightning flash that is less than 8 km distant (i.e., events masquerading as ECs) is calculated based on the rate of TETRA triggers (due mainly to cosmic ray showers), the live time, and the duration of storm activity. The storm activity time is taken to be the sum of all time windows where there was lightning within 8 km and 7 s, and there was no electronic noise or other instrumental problems. For a total storm time of 12.65 h, we calculate the expected number of ECs due to accidental triggers to be 0.82. This assumes 100% lightning detection efficiency. The efficiency of the USPLN in our area has not been tested; however, if we assume a similar sensitivity to that measured by Jacques *et al.* [2011] for cloud-to-ground lightning with peak current in excess of 20 kA of approximately 25% to account for undetected lightning flashes, then we would expect 3.3 accidental ECs compared to the 14 observed.

[22] Figure 4 compares data acquired within 7 s of lightning to the remaining data with accurate timing information. The distribution of events versus σ within 7 s of a USPLN lightning strike within 8 km is shown in black. The significance distribution of the remaining data has been normalized to the total storm activity time of the lightning distribution for comparison, shown in grey. The excess of events above 20σ in the lightning distribution (black) as compared to the normalized distribution (grey) indicates the association of the gamma-ray events with nearby lightning. (Note that since three events involve seven separate coincident triggers in individual detector boxes, there are 18 individual triggers shown in Figure 4 compared to the 14 ECs with accurate timing information in Table 1.) A Kolmogorov-Smirnov test of the two distributions results in a D parameter of 0.25, corresponding to high confidence that the two distributions are distinct.

[23] The dark solid line in Figure 5 shows the deposited energy spectrum of the 24 event candidates, with events

Table 1. Properties of the 24 Event Candidates^a

Date	Trigger Time (CST) (hh-mm-ss)	Max Lightning Rate/Second Within 8 km	Cloud Density (dBZ)	Number of Flashes Within 8 km and 5 min	Trigger-Lightning Difference (ms)	Lightning Distance (km)	Lightning Current (kA)	T_{90} Duration (μ s)	Total γ -Rays Detected	Total Energy (MeV)	σ Above Mean	Prob. of CEC
31 July 2011	16-21-44.976	2	45	12	-6	2.3	-43.6	702	22	14.7	25.2	1.7E-06
31 July 2011	16-21-45.300	2	45	12	-4	2.9	-29.1	1326	24	11.7	25.2	1.7E-06
18 August 2011	17-57-38.984	4	50	40	6743	2.1	-23.4	1318	40	20.3	22.5	1.2E-13
24 February 2011	23-11-15.787	3	45	1	-6	4.7	-20.9	953	20	1.7	24.6	-
29 July 2011	10-38-58.932	6	45	42	5	0.6	-57.7	153	8	4.8	23.0	-
18 August 2011	17-57-39.202	4	50	40	6525	2.1	-23.4	24	7	3.6	26.1	-
12 March 2012	11-30-16.500	6	45	4	5	2.6	-81.3	1997	7	3.2	21.8	-
2 April 2012	12-29-30.554	3	50	8	6	1.0	-29.9	464	30	31.6	104.3	-
4 April 2012	02-49-21.900	5	55	21	-3	3.1	-158.4	515	24	21.3	88.6	-
5 August 2012	14-43-35.661	7	40	16	-849	1.0	-56.5	392	18	12.4	40.6	-
6 August 2012	19-17-33.359	5	50	1	1017	1.3	-23.1	465	13	4.5	21.9	-
9 August 2012	15-27-29.804	4	50	21	2	0.6	-27.8	2412	12	2.9	29.0	-
9 August 2012	15-28-36.070	4	50	27	80	1.4	-36.7	4217	24	7.4	41.3	-
9 August 2012	15-28-36.560	4	50	27	2	1.3	-19.2	146	12	8.0	33.9	-
6 June 2012	15-44-18	6	55	16	-	-	-	609	14	8.5	45.7	-
6 June 2012	15-37-31	6	55	40	-	-	-	865	45	27.2	86.1	-
6 June 2012	19-23-27	6	55	40	-	-	-	2979	18	6.7	45.7	-
6 June 2012	19-29-43	6	55	33	-	-	-	2376	24	9.7	55.3	-
6 June 2012	19-31-21	6	55	19	-	-	-	919	40	29.8	48.3	-
6 June 2012	19-32-41	6	55	19	-	-	-	827	9	5.4	21.0	-
6 June 2012	19-36-40	6	55	18	-	-	-	2035	8	5.2	20.1	-
6 June 2012	19-36-41	6	55	18	-	-	-	631	32	31.4	63.1	-
9 June 2012	13-40-16	6	50	1	-	-	-	1930	15	8.6	55.1	-
7 July 2012	17-38-45	5	45	1	-	-	-	510	14	8.0	33.9	-

^aCECs are listed in the top section; ECs for which the absolute timing uncertainty is known are listed in the middle section; and ECs for which the absolute timing uncertainty is unknown are listed in the bottom section of the table. The date and time of each EC trigger are listed, along with the properties of the storm associated with each event. The properties of the associated lightning, event duration, number of gamma-rays detected, total energy, and event significance are also listed for each event. The probability of each CEC occurring is listed in the last column for the CECs.

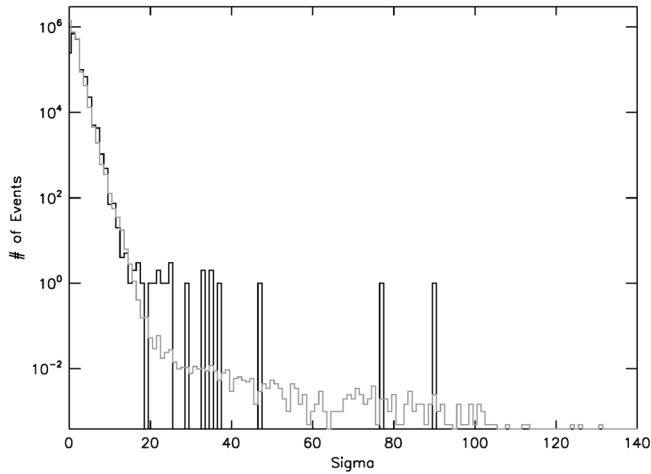


Figure 4. Distribution of events with significance σ . Distribution of events within 7 s of nearby (< 8 km) lightning is shown in black. Distribution of all data, normalized to 0.52 days of live time, is shown in grey, showing excess of lightning-associated ECs at $\sigma > 20$.

observed up to 2.7 MeV deposited energy. It should be emphasized that with TETRA's thin detectors, only a portion of the incident gamma-ray energy is actually detected. Between 200 keV and 1.2 MeV, the EC spectrum is fit with a power law $E^{-\alpha}$, with $\alpha = 1.20 \pm 0.13$ and $\chi^2/\text{degree of freedom} = 0.4$ (dashed dark line). On the same figure, the grey line shows the spectrum of non-EC triggers (i.e., triggers not associated with lightning within 5 mi and 7 s); this spectrum is softer, with a best fit power law index $\alpha = 1.79 \pm 0.04$ and $\chi^2/\text{degree of freedom} = 1.0$ (dashed grey line). The associations of the events reported here with negative polarity lightning strikes and the low likelihood that these are background events, along with the durations observed, are indicative of downward directed TGFs produced by the RREA mechanism.

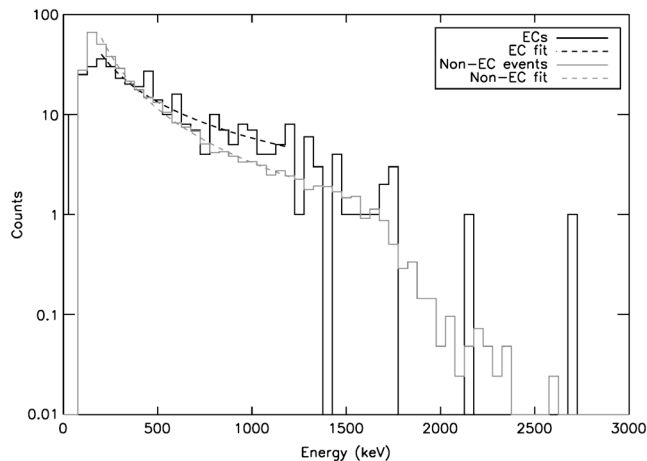


Figure 5. Spectra of event candidates and non-EC TETRA triggers. Spectrum of ECs is shown in black. Spectrum of non-EC TETRA triggers (triggers not associated with lightning nearby in time and distance) is shown in grey. Power law fits between 200 keV and 1200 keV of the form $E^{-\alpha}$ are shown with dotted lines, where $\alpha = 1.20 \pm 0.13$ and 1.79 ± 0.04 for EC and non-EC events, respectively.

[24] In three of the 24 ECs, triggers were recorded in two or more boxes separated by ~ 1000 m within less than ± 2 ms. This is approximately the relative timing accuracy between separate boxes. All three of these coincident event candidates (CECs) occurred in July and August of 2011, when storms in southern Louisiana tend to be associated with disturbances in the Gulf of Mexico rather than frontal lines. No CECs were detected when there was no lightning activity within 8 km.

[25] Time histories for the three CECs are shown in Figure 6. The plot shows a 50 ms window centered on the event trigger time, defined as the center of the first 2 ms bin containing a trigger. The counts for each box (i.e., the number of phototubes detecting a signal with amplitude in excess of 50 keV within the $1 \mu\text{s}$ PMT anode output integration time) are plotted versus time relative to the event trigger time. For the two events on 31 July 2011 (Figures 6a and 6b), the lightning strikes closest in time occurred within approximately 6 and 4 ms of the event trigger. For those cases, the time of the lightning strike is shown as a cross with a timing uncertainty of ± 2 ms near the top of the plot. In the first 31 July 2011 event (Figure 6a), one PMT in Box 3 fired, followed by two PMTs in Box 4 2.3 ms later. The distance between the two boxes was 1500 m, corresponding to a gamma-ray travel time difference of up to $5 \mu\text{s}$. In fact, we believe the differences between the event times in the separate boxes in Figure 6 are a direct measure of the absolute timing differences between the boxes.

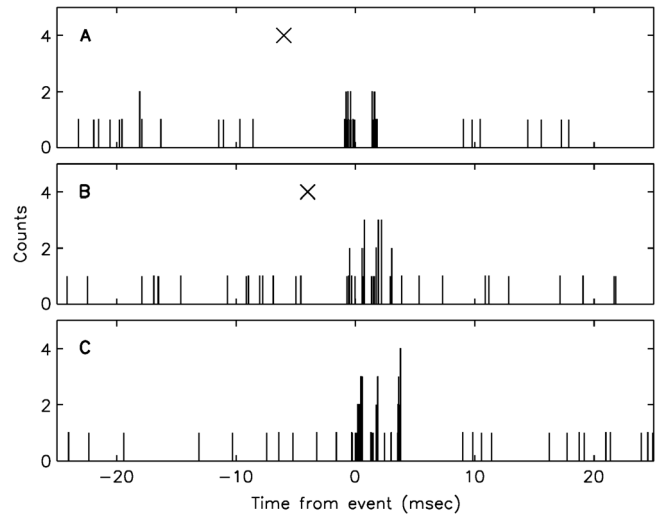


Figure 6. NaI time histories over 50 ms window centered on the trigger time for each CEC. Lightning strikes within 8 km in the 50 ms window have a ± 2 ms timing uncertainty and are shown with crosses. Figure 6a shows the CEC event on 31 July 2011 at 16:21:44.976 CST. The Box 3 time history is centered at 0 ms and Box 4 at 2 ms. A USPLN lightning strike within 8 km is indicated by the cross at -6 ms. Figure 6b shows the event on 31 July 2011 at 16:21:45.300 CST. The Box 3 time history is centered at 0 ms and Box 4 at 2 ms. A USPLN lightning strike within 8 km is indicated by the cross at -4 ms. (c) The event on 18 August 2011 at 17:57:38.984 CST with the Box 3 time history centered at 0 ms, Box 1 at 2 ms, and Box 4 at 4 ms. No USPLN lightning was detected within 8 km within this 50 ms window.

[26] The expected number of CECs due to random triggers is small: Given an initial EC with counting rate in one box in excess of 20σ above the daily average, the likelihood that a second or third trigger occurred at random in another box within the timing uncertainty of 2 ms on the same day is estimated as $(4 \text{ ms} \times N/86,400 \text{ s})^{b-1}$, where N is the total number of random 20σ triggers detected per day through February 2013 and b is the number of boxes triggered in the event. (For simplicity, we neglect here the increase in trigger rate during a thunderstorm shown in Figure 1.) Multiplying by the number of ECs then gives the expected number of spurious CECs involving two boxes occurring by chance as 1.7×10^{-6} , as listed in Table 1.

[27] A composite energy spectrum summed over the three CECs is shown in Figure 7. A total of 80 gamma-ray pulse heights above 50 keV and within the T_{90} interval of each coincidence trigger are shown. The average photon energy detected is approximately 0.5 MeV, an energy at which the fraction that passes through a nominal 1.6 km of atmosphere at ground level (STP) without interaction is $\sim 10^{-7}$. This average energy is low compared to the typical energies observed by the orbiting detectors [Dwyer *et al.*, 2012a] and is presumably biased to low energies by the 0.5 cm thickness of the TETRA NaI scintillators.

[28] Figure 8 shows the distance from the detectors and the measured current for each lightning flash within 8 km of TETRA from 1 July 2010 to 28 February 2013. There were a total of 5360 flashes within 8 km. For each of the 10 ECs and CECs with lightning within 8 km and ± 100 ms of the trigger time, the distance and measured current are plotted with black crosses. Although all the TETRA events correspond to lightning less than 5 km away, the two lightning flashes within ± 100 ms of a CEC are both more than 2 km away. No CECs were detected with closer events. If all discharges produce TGFs [Østgaard *et al.*, 2012], then the rate of detection and the CEC distances point to either a range of intensities extending below the sensitivity limit of TETRA, strongly nonisotropic emission, or the possibility that the gamma-ray emission is only indirectly associated with the lightning

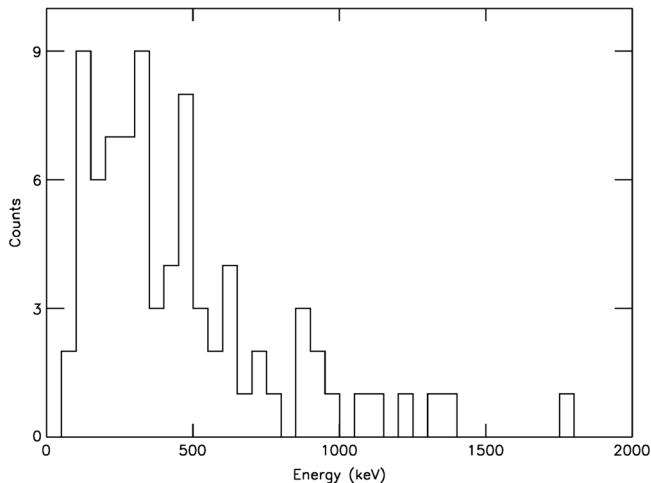


Figure 7. CEC event spectra. Combined NaI detector energy spectrum for the three CECs. Eighty photons were detected within the T_{90} interval of each individual detector box's trigger time.

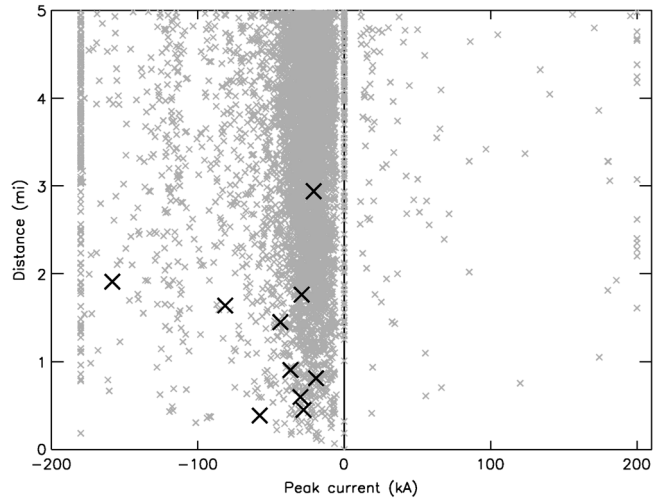


Figure 8. All lightning activities within 8 km of TETRA from 1 July 2010 to 28 February 2013. The current and distance for all USPLN lightning flashes within 8 km of TETRA are indicated by grey crosses. Lightning strikes that are within 8 km and 100 ms of an EC or CEC are considered coincident strikes and are plotted with black crosses. The vertical line at 0 kA indicates IC lightning.

[Connaughton *et al.*, 2013]. This can also occur if some gamma-ray events are produced by intracloud (IC) strikes, since the USPLN data record primarily cloud-to-ground strikes.

[29] Out of the 10 ECs shown in Figure 7, nine were found to be within 6 ms of a negative polarity CG lightning strike within 5 km with current above 20 kA (Table 1). For the two CECs that occurred on 31 July 2011, lightning strikes are recorded at 6 ms and 4 ms before the TETRA triggers. In both cases, these were nearby, cloud-to-ground events at 2.3 km distance with current -43.6 kA and 2.9 km distance with current -29.1 kA. For four ECs with accurate timing information, the lightning strikes closest in time to the TETRA triggers were in excess of ± 100 ms before or after the NaI signal and so are not considered coincident with a USPLN observed strike. Again, this can occur if some gamma-ray events are produced by intracloud (IC) strikes or if the gamma-rays are not all directly associated with the lightning.

4. Conclusions

[30] The gamma-ray events described here have durations ranging from 24 μs to 4.2 ms. The similarity of these event durations observed by TETRA to those reported by BATSE, RHESSI, AGILE, Fermi, and ICLRT suggests that the TETRA events are also generated by the RREA mechanism. Dwyer *et al.* [2012b] compared the spectrum of X-rays from lightning to gamma-rays from TGFs, showing a marked difference above 2 MeV, but the restricted energy range of TETRA and the low statistics make it impossible to draw strong conclusions from the observed TETRA spectra.

[31] Fermi GBM data suggest that WWLLN detects shorter duration TGFs more efficiently than the longer ones because of the frequency constraints of the network (between 6 and 18 kHz). For the sferic signals found within a 400 μs window around the TGF gammas, the stronger sferics appear due to the TGF itself while the weaker sferics are due to associated +IC

lightning [Connaughton et al., 2013]. The brightest TGFs seen by BATSE, RHESSI, and GBM produce $\sim 10^{17}$ runaway electrons with a source altitude ~ 13 km [Briggs et al., 2010]. In contrast, the two TGFs previously reported from the ground by ICLRT are associated with $-CG$ lightning [Dwyer et al., 2004, 2012b]. The 2009 ICLRT event produced $\sim 10^{11}$ runaway electrons and was observed at a distance of ~ 2 km. If the TETRA events are characterized by typical energy 500 keV and distance 1.6 km, then atmospheric absorption attenuates the flux by a factor of $\sim 4 \times 10^{-8}$ at sea level. Assuming isotropic emission at a distance of 1.6 km, a typical total of 20 photons observed in an event by TETRA then requires in excess of $\sim 10^{18}$ photons at the source. Either the ground level TETRA events are beamed or they are distinctly different from the ICLRT events.

[32] Here we have presented data for a series of gamma-ray events observed with a self-triggered ground array, suitable for observing weak events from nearby distances without a bias caused by a lightning trigger, and find that events with durations < 5 ms and detected individual photon energies up to at least 2 MeV appear to be produced in conjunction with nearby $-CG$ lightning. In two CECs, these are most closely associated with $-CG$ events 2.3 and 2.9 km away. In the other CEC event, the nearest detected lightning strike in time is more than 6 s after the gamma-ray event. Either this gamma-ray event is not correlated with nearby lightning, the associated CG lightning strike was missed by the lightning network, or the event was due to IC lightning that was not detected by the lightning network.

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