Observation of Ground Level Gamma-ray Showers in Coincidence with Downward Lightning Leader

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AtmoHead 2018
Capri, Italy
**TERRSTIAL GAMMA RAY FLASHES**

- Rare phenomenon that happens in ordinary thunderstorms.
- Observed by orbiting instruments (BATSE, RHESSI, FERMI, AGILE)
- Duration of tens of us to ms.
- Generated during the initial negative breakdown stage of IC lightning
  
  $10^{-14} - 10^{-19}, \ E > 100 \text{KeV}$
• Is there a counterpart to this phenomenon?

• Can we obtain quantities at the generating TGF sources?
Dwyer et al, JGR 117 A10303 (2012)

- **Ground-Based TGF#1**
- **20090630**
- During natural 99kA – CG return stroke
- 191 μs after start of ground stroke
- 19 γ's, individual energy measurements
- *X-rays prior to ground stroke, TGF after.*
- **Ultra-High Energy Cosmic Ray Detector**: $10^{18} \rightarrow 10^{20}$ eV and higher
- TA Surface Detector (TASD): 507 scintillation detectors, 1.2 km grid, covering 700 km².
- Mean altitude 1400 meters MSL
- Operation since March 2008

Millard County, Utah U.S.A.
SCINTILLATION COUNTERS

- 2 layers of 3m² plastic scintillators, separated by steel sheet in ground steel box
- Autonomous, 24/7 operation
- GHz WLAN readout
- Typically 1 trigger/2 minutes
TA Observation: “Burst” Events

- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers, < 1 msec
  - Occasional Dt ~ 10 msec
- “Normal” SD trigger rate < 0.01 Hz. These cannot be cosmic ray air showers.
- Found to have close time/space coincidence with U.S. National Lightning Detection Network (NLDN) activity.
LIGHTNING MAPPING ARRAY

- 9 LMA Stations
- 60 km in diameter
- RF quite locations
- Rural areas away from buildings
- E-measuring slow antenna.

In operation since 2013
How Lightning Mapped

- Detect impulsive radiation within 80 us window in the band bet 60-66 MHZ.
- multiple detectors to determine their x,y,z,t
- Avoid misconstruction >= 6 receivers are used.
- Locate hunders to thousands of sources per flash
Slow antenna

- GPS-timed capacitor, read out with 10 s time constant.
- Record electric field between 10 mV/m and 10 kV/m
NATIONAL LIGHTNING DETECTION NETWORK (NLDN) DATA BASE

- Lightning time
- 2D Coordinates (Latitude and Longitude)
- Peak Current (kA)
- Polarity (+/-)
- Could-Cloud (50-60% efficiency)
- Cloud-Ground lightning (90% efficiency)
Observations
can we obtain quantities at the generating TGF source?
TA/LMA “Flash 1”

- Occurred at the first 1 ms of the flash, ~200 ms before CG hit
- Occurred as a negative breakdown with a leader height between 4–5 km AGL
- TASD waveform has 400 $\mu$s duration with 10s of $\mu$s in sub-pluses
• Different Flash same day
• Occurred as a negative breakdown with a leader height between 3–4 km AGL
• TASD waveform has 400 μs duration with 10s of μs in sub-pluses
ΔE ("Slow Antenna") Measurements

- (4/7 events shown here)
- Overall, similar "message" as LMA events
  - First ms of IC/CG flash
  - Moderate and energetic leaders
Are we seeing downward TGFs?

- Photon absorption length plateaus at few 10's g/cm² above ~100 keV.
- ~100's of meters @ TA elevations
- Few of the primary photons make it to the ground!
• GEANT4 Simulation: TASD response to RREA-Photon Spectrum at Altitude, including atmosphere.
• Mean energy deposit at low energy falls off much faster than reasonable spectra (i.e. RREA)
• Conclude that primary photons responsible for TASD signal must be > 1 MeV at altitude.
Comparison
Number of photons

Sources on “low end” of TGF estimates
- Would be below satellite triggering threshold!
Comparison with other observations

Celestian and Pasko (2012)

- Overall duration of SD bursts comparable to observed TGF $\Delta t$
- Discrete subevents from few to few 10's of $\mu$sec.
  - We're viewing sources from $\sim1/100^{th}$ the distance
  - Before Compton "smearing"
**Gamma Ray Showers Observed at Ground Level in Coincidence With Downward Lightning Leaders**


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3Department of Physics, Tokyo University of Science, Noda, Japan, 4Department of Physics, Kinki University, Higashi-osaka, Japan,
First observation of TGF with slow antenna, LMA, TASD, and NLDN

• \(9 \times 10^5\) m/s.
• Multiple IC observations followed by an energetic CG with peak current of -113kA.
TA x 4 Project

- world largest sample of downward observed gamma rays.
- we will have 10 Events per year.
BREAKING NEWS!
Interferometer
Slow antenna

- GPS-timed capacitor, read out with 10 s time constant.

- Record electric field between 10 mV/m and 10 kV/m
Fast Antenna

Initial Breakdown Pulse region
Is this the origin of TGFs?

Return stroke

ΔE
Leader Stage

VHF
Fast $\Delta E$
“spherical"

Initial Breakdown Pulse region
Is this the origin of TGFs?

P.Krehbiel *et al*

Return stroke
Preliminary
SUMMARY

- observed 25 TASD bursts in coincidence with lightning (world largest sample of downward observed gamma rays).
- 15 observed with LMA or slow antenna.
- Originate TGF observations to the IBPs of lightning.
- Forward-beamed showers of $10^{12}$-$10^{14}$ primary photons.
- First observed event with INTF and Fast antenna correlating observed TGF with two particularly energetic leader steps.
• 1VEM ~ 30 ADC
• 1 ADC count ~ 70 keV
• Photon 170 keV
SD response: $\gamma$ and $e^\pm$

**Diagram:**
- Gamma rays ($\gamma$) and electrons ($e^\pm$) interacting with scintillators and steel plates.
- GEANT4 simulation.

**Graphs:**
- Mean energy deposition vs. incident energy (MeV) for electrons and photons.
- Cosmic ray core waveform.
- Leader-coincident core waveform.
Are we seeing downward TGFs?

- Photon absorption length plateaus at few 10's g/cm² above ~100 keV.
- ~100's of meters @ TA elevations
- Few of the primary photons make it to the ground!
GEANT Simulation of Atmosphere and TASD

- US standard atmosphere
• GEANT4 Simulation: T ASD response to RREA-Photon Spectrum at Altitude, including atmosphere.

• Mean energy deposit at low energy falls off much faster than reasonable spectra (i.e. RREA)

• Conclude that primary photons responsible for T ASD signal must be > 1 MeV at altitude.

- **Ground-Based TGF #2**
- **20140613**
- During natural 224 kA – CG return stroke
- **191 μs after** peak of ground stroke
- **6 γ's ≤ 5.7 MeV**
- **No radiation prior to ground stroke, TGF after.**
TA/LMA “Flash 3”

- Isolated event May 2016
- TASD triggers in 2\textsuperscript{nd} ms of flash. Ground stroke occurs rapidly after.
- Suggests a somewhat different “energetic leader” event propagating rapidly to ground.
- Consistent with exponential growth of SD pulse heights with time.
Dwyer et al, JGR 117 A10303 (2012)

Gamma Rays

“x-rays from lightning”
SD response: g and $e^\pm$

Cosmic ray core waveform

Leader-coincident core waveform

TASD is optimized for high-energy charged particles:
- inefficient for photons
- but this is what photons would look like!
TASD Waveforms, Flash 1, 2, 3

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**FL1:** 2015/09/15 12:13:04  SD0604 303 VEM

**FL2:** 2015/09/15 19:37:01  SD1423 225 VEM

**FL3:** 2016/05/10 02:41:50  SD0922 26,418 VEM

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**ADC counts**

**Time after first trigger (μs)**
# TELESCOPE ARRAY (TA/LMA)

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<th>TASD</th>
<th>$\gamma$-ray SD</th>
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<td>Plastic scintillator</td>
<td>Mainly NaI accompanied gas-counters</td>
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<tr>
<td>Lower SD number density</td>
<td>Higher SD number density</td>
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<tr>
<td>300 Times larger</td>
<td>Smaller in size</td>
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<td>10 times faster response</td>
<td>Slower response</td>
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“Flash3” Event 20160510-024150
“Flash 2” Event 20150915-193701

NLDN - 12 kA IC
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Cosmic Ray Shower (top) and “Burst” Event

![Graphs showing ADC counts and distance plots with time intervals and intensity levels.](image-url)