Terrestrial Gamma-Ray Flashes

M.Tavani
(INAF and Univ. of Rome Tor Vergata)
TGFs from space: discovered by CGRO-BATSE

76 TGFs in 9 years
4 energy channels.
(Fishman et al., Science, 1994)
Observations of TGFs from Four Spacecraft:

1. Burst and Transient Source Experiment (BATSE) / Compton Observatory (CGRO) 1991-2000


3. MCAL and GRID on AGILE (launched Apr. 23, 2007)

TGFs from BATSE  (from Fishman et al., 1994)
GLOBAL FLASH RATE - ANNUAL

(OTD & LIS DATA)

(from J. Fishman)
Terrestrial Gamma-ray Flashes (TGFs)

- Gamma-ray flashes with incoming direction compatible with the Earth surface. Discovered by BATSE (Fishman et al., Science, 1994).
- Few millisecond typical duration; hard spectrum (up to tens MeV).
- Detected by RHESSI up to 20 MeV (Smith et al., Science, 2005).
- Clearly associated to lightning discharges during thunderstorms by means of correlation with VLF sferic waves detection on ground (Inan et al., GRL, 1996; Cummer et al., GRL, 2005).
Terrestrial Gamma-ray Flashes (TGFs)

Geophysical phenomena observed from space by instruments designed for gamma-ray astrophysics

Challenging detection: timing and energy range are key issues
TGFs detected by RHESSI (Cohen et al. 2010)
2005: RHESSI detection up to 20 MeV

Smith et al., Science, 2005

- Continuous time-tagged event list
- NO ON-BOARD TRIGGER LOGIC
- 10–20 TGF per month
- Typically 20-30 counts/TGF
- ~800 TGFs reported in the 1st RHESSI TGF catalog (Grefenstette et al., JGR, 2009)
• **Sprites:**
  - Flashes in the mesosphere
  - 10-100 ms duration
  - Generated from +CG
  - Primarily red

• **Jets:**
  - Injected from cloud tops
  - 100-1000 ms duration
  - Generated with or without CG activity
  - Primarily blue

• **Elves**
  - Rings of emissions at lower edge of the ionosphere
  - 1-10 ms duration
  - Stimulated by electromagnetic pulse from lightning
  - Primarily red

[Neurbert 2003]
TGFs originate at ~ 10-20 km
RHESSI TGF Bremsstrahlung spectrum absorbed Relativistic Runaway electron spectrum (Dwyer & Smith 2008)

Flattening of spectrum @ 1 MeV requires production altitude 10-20 km: near tropical tropopause (just above thunderclouds)

Dwyer & Smith 2005
Carlson, Lehtinen and Inan 2007
not easy to propagate up to 550 km

selection effects important
NCEP/NCAR tropopause height map, January, overlying air mass (in g/cm²)

Gamma-ray transmission map based on tropopause height data (MC)

Difference between HESSI TGF map and transmission-corrected map

(from D. Smith et al., 2010)
Figure 9. Histograms of tropopause pressure (mbar) for TGFs (gray) and lightning (black), showing the preference of TGFs for high altitudes.
Figure 10. Position of the six TGFs with tropopause pressures >140 mbar; see Figure 5. The brightness scale beneath is another rendering of the LIS/OTD map (Figure 4a).
Mechanisms of air breakdown (decreasing E) (Smith 2008):

**Cold runaway**
*Any e- goes relativistic*

**Conventional (Townsend)**
*Ionization > attachment*

**Streamer**
*Self-propagating*

**RREA (Relativistic Runaway Electron Avalanche)**
*Rel. seed electron(s)*

**Leader**
*Thermal ionization*

Frictional force produced by the motion of electrons through air.
what makes AGILE unique for TGFs:

- Only instrument in equatorial orbit
  - low-background
- Only instrument with sub-msec trigger capability
- Instrument with the best capability at $E > 30-40$ MeV
AGILE: inside the cube…

ANTICOINCIDENCE

HARD X-RAY DETECTOR (SUPER-AGILE)

GAMMA-RAY DETECTOR

SILICON TRACKER

(MINI) CALORIMETER
30 CsI(Tl) bars with Photodiode readout
1400 cm$^2$ geometrical area
~300 cm$^2$ effective area @ 1 MeV
330 keV – 100 MeV energy range
14% energy resolution FWHM @ 1.3 MeV
2 $\mu$s timing accuracy in photon-by-photon mode
Clever, fully-programmable trigger logic on time scales from 8s to 16ms, 1ms and 300$\mu$s

Labanti et al., NIM A (2009): instrument paper
Fuschino et al., NIM A (2008): trigger logic
Marisaldi et al., JGR (2010): TGF detections
Example of a TGF detected by AGILE
(early) AGILE/MCAL TGF cumulative spectrum (2009)

Cutoff PL model:

\[ F(E) \sim E^{-\alpha} e^{-E/E_0} \]

\[ \alpha = 0.4 \pm 0.3 \]

\[ E_0 = 8.5 \pm 1.6 \text{ MeV} \]

red. \( \chi^2 = 1.4 \)

(18 d.o.f.)
AGILE high energy results:

- Localization of TGFs in gamma-rays from space
- High energy spectrum

Credit: Alan Stonebraker
Operating TGF detectors

effective area vs. energy

Data from: Smith et al. (2002), Meegan et al. (2009), Labanti et al. (2009), Tavani et al. (2009)
MCAL TGF detection rate

> 300 class A TGFs + ~200 class B TGFs since June 2008

~10 class A TGF/month
~5 class B TGF/month

24 months 1st AGILE TGF catalog in preparation

34 TGFs Published in M. Marisaldi et al., J. Geoph. Res., 115, A00E13, 2010.
• AGILE special trigger capability
• MCAL burst search from sub-ms to seconds
  – TGFs detected by the trigger logic working in the timescale range $0.3 \text{ ms} < \tau < 16 \text{ ms}$

*** about 600 TGFs detected since 2009

*** about 300 are with good S/N ratio
energy range 0.4 – 100 MeV
a number of issues

• high-energy range above 30-40 MeV
• discovery in 2010 of a substantial power-law contribution to the spectrum above 40 MeV
  – origin ???
  – what kind of TGFs ?
  – what is the largest photon energy emitted by TGFs ?
  – impact of HE-TGFs
The AGILE TGF sample

Average properties
A AND B class:

Number of counts = 14 +/- 9

Duration (= 0.8 +/- 0.4) ms

Energy = (4.0 +/- 1.7) MeV
LIS/OTD global lightning distribution (10 Years of data)

Flash rate \[ \text{fl/km}^2 \text{year}^{-1} \]

MCAL exposure [Seconds per bin] (Mar 2009 - Feb 2010)

Trigger logic really active

2.5 x 1.0 deg [lon x lat]

Lightning distribution multiplied by the MCAL exposure to direct comparison with 12 Months of AGILE TGFs

LIS-OTD high resolution full climatology available at http://thunder.msfc.nasa.gov/

0.68 correlation coefficient for a global fit

F. Fuschino et al. 2011

LIS-OTD high resolution full climatology available at http://thunder.msfc.nasa.gov/
<table>
<thead>
<tr>
<th>Continental region</th>
<th>TGF / flash ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>America</td>
<td>$1.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>Africa</td>
<td>$6.0 \times 10^{-5}$</td>
</tr>
<tr>
<td>South East Asia</td>
<td>$7.5 \times 10^{-5}$</td>
</tr>
<tr>
<td>All</td>
<td>$7.8 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

(F. Fuschino et al. 2011)
• Assuming the spread of TGF / flash ratio holds at all latitude, and considering 44 ± 5 flash/s (Christian et al. 2003), we obtain 220 ÷ 570 TGFs / day, in agreement with Carlson et al. 2009.

  Fuschino F., et al., GRL (2011)

• The excess of TGFs over Central America and South East Asia with respect to Africa is confirmed (Smith et al., 2010)

• The high degree of correlation obtained for South East Asia suggests that global lightning activity over this region is by far a better proxy for TGFs than on other continental regions. Climatic effect? (Splitt et al., 2010)

• Thanks to the low inclination orbit AGILE provides the highest TGF detection rate surface density, good for seasonal/annual variability studies
Imaging TGFs from space

(Marisaldi et al. 2010)

- MCAL is detecting TGF photons up to 100 MeV
- why don’t we look at detections by the AGILE gamma-ray imager (GRID) sensitive above 20 MeV?
- It would be the first direct localization of TGFs in gamma-rays
direct imaging of TGFs from space (using γ-rays !)  
(Marisaldi et al. 2010)


13 GRID events within 2 ms from TGFs T0!
Imaging TGFs from space with the AGILE GRID

Two ways to bypass it...
1. Albedo filtering disabled
~ 100 days between 2008 – 2009 for test purposes

**Forward events.**
It cannot be used because of telemetry limitations
2. the albedo filter logic is not optimized for events from below, which can be taken as originating from the front side.

So, events coming from the Earth can be accepted: “Reverse events”
AGILE TGF 12809-19
(2010 Oct. 16 20:44:55 UT)

AGILE pointing

“reverse event”
direction
(TGF source)
Geographical distribution of a subset

AGILE footprint
GRID gamma-ray projection

Reverse event direction (TGF source)

GRID pointing

Credits: B. Carlson, Univ. Bergen

GOES IR image ~5 minutes before TGF

TRMM-LIS pass ~1 hour earlier
# 14008

High E MCAL 58 MeV
AGILE TGF reconstructed positions

Event clustering at < 400 km from AGILE footprint
Consistency with previous detections based on RHESSI TGFs and sferics
(Cummer et al., GRL 2005, Cohen et al., GRL 2010)

TFG cumulative spectrum


110 TGFs  26 events $E_{\text{max}} > 20$ MeV

broken power-law model $\beta = 2.7$

RREA cutoff power-law model

significant detection of $\gamma$-rays with $E>40$ MeV unexplained by standard RREA models: a challenge for emission models
High energy events

M. Marisaldi
Issues and impact

origin of TGF high-energy emission up to 100 MeV, a challenge to current RREA models, a very efficient accelerator!

lightning-TGF connection: which lightning?

how often do TGFs occur? mapping, monitoring… local climate, climate change connections

impact of TGFs HE-emission on the atmospheric environment: chemistry, radiation effects

electrons, gamma-rays, neutrons
neutron production, simulation

source at $h = 3800$ m
ground at $3200$ m a.s.l

(A. Pesoli, F. Palma, M.T., 2012)