The First Terrestrial Electron Beam Observed by The Atmosphere-Space Interactions Monitor (ASIM)

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Introduction
Introduction: Terrestrial Electron Beam

- **Terrestrial Gamma-ray Flashes (TGF)**
  - Discovered from space observations in early 90's *(Fishman et al., 1994)*
  - Correlated to thunderstorms
  - Duration of 20 us to 2 ms
  - Energies up to 30-40 MeV
  - Production altitude of 10 to 15 km

- Less than 2% of initial photon content can reach space

- Production of large amounts of
  - Electrons (Compton scattering + pair production)
  - Positrons (pair production)

- A small fraction can reach space: propagation in ionosphere, magnetosphere
  - "beamed" by Earth's magnetic field
  - First report using BATSE data *(Dwyer et al., 2008)*
  - Then detected by Fermi, and BeppoSAX

![Production rate altitude profile](chart.png)
• 400 km altitude: Electrons/positrons are spread inside an ellipse, that is \( \sim 88 \times \sim 54 \) km for this event (95% content)

• much longer than TGFs (\(~2\) to \(~20\) times)

• TEB time duration is affected by the distribution of electrons' pitch angles when escaping the atmosphere
The observation
- ASIM event of September 16th, 2018, at 13:14:44.733601 (UTC)
- Duration ~ 4 ms
- WWLLN: network of VLF receivers that records time and position of lightning discharges
- Best WWLLN match:
  - ~5 ms after event
  - (MXGS absolute timing uncertainty ~ 20 ms)
  - (WWLLN uncertainty +/- 50 us)
- No lightning activity below the ISS
- Lightning activity close to the north magnetic field line footpoint!
- No lightning activity close to the south magnetic field line footpoint
- ISS to North Magnetic Foot Point distance ~ 650 km
- Image from GOES-16 (geostationary imager), 45 seconds after the event
Image from GOES-16 (geostationary imager), 45 seconds after the event
TEB event: map

- Best WWLLN match:
  - ~12 km away (Lat = 11.08°, Lon = -95.29°) (WWLLN localization uncertainty +/-15 km)
  - ~5 ms after event (MXGS absolute timing uncertainty ~ 20 ms)

-> TGF/TEB's parent lightning discharge discharge

Image from GOES-16

magnetic foot point at 40 km altitude

magnetic foot point at 50 km altitude

WWLLN (+/- 6 ms)
Monte-Carlo Simulations
Simulation strategy

- **2 stages:**
  -> 1. **Propagation** from 15 km altitude to satellite (~400 km)
    - Two models were used, based on Monte-Carlo methods:
      - MC-PEPTITA (*Sarria et al., 2015*)
      - A new Geant4-based model (*made available, see end of talk*)
    - Both gave similar results for this case
  
- Include atmosphere (NRL-MSISE00) and magnetic field (IGRF-12)

- **All relevant processes:**
  - **photons**: Compton scattering, pair production, rayleigh scattering, photo-electric absorption
  - **electrons**: inelastic and elastic scatterings, bremsstrahlung
  - **positions**: electrons' processes + annihilation

-> 2. **Detector response**
  - i.e. propagation to HED's BGO crystals. See next.
Models used

1. ASIM + Columbus Mass model (courtesy B.E. Carlson)
- **TEB are long event, with ~10 times lower flux (counts/time) than TGF:** no instrumental effect that could make the spectrum unreliable

Critical value $\chi^2_{red,c} = 2.0$

- TGF photon spectrum is incompatible
- TEB spectrum is compatible

Scaled to minimize $\chi^2_{red}$

$\chi^2_{red} = 6.25$

$\chi^2_{red} = 0.95$
Lightcurve simulation

- Travel time from production (15 km) to satellite (400 km): ~ 2.2 ms
- TEB response *gives a better explanation*, but
  - MXGS probably detected some of the parent TGF
  - TEB about 30 times greater flux
- Photon/electron ratio strongly dependent on TGF angular distribution
Lightcurve fitting

- Recorded photon quantity changed by adjusting the TGF beaming parameters
- Best fit for $20° < \sigma_\theta < 30°$ -> consistent with previous works (e.g. Hazelton et al., 2009)
- Parent TGF photons is ~ 5 to 10 % of detected counts
log10(number of photons required at source)

- $10^{17.3}$ to $10^{18.8}$ required at source, in agreement with previous studies (e.g. Dwyer & Smith, 2005; Dwyer et al., 2012; Cummer et al., 2014; Gjesteland et al., 2015)
Conclusions / future work

- ASIM detected an unusually long TGF: > 4 ms
- **No lightning activity closeby**, but near the northern magnetic foot point
- Good WWLLN match around northern magnetic foot print (point)
- Parent TGF was produced in the vicinity of an overshooting top of a thunderstorm
- Monte-Carlo simulations results:
  - *Lightcurve* and *spectrum* are explained by TEB rather than TGF
    - **Angular distribution**: $20^\circ < \sigma_\theta < 30^\circ$
    - **TGF source intensity**: between $\sim 10^{17}$ and $\sim 10^{19}$ photons

Future:
- TEB events with **better instrumental coverage**? (here, LED and MMIA were off)
  - **ASIM's LED ~ twice more sensitive than ASIM's HED**
  - low energy part of the spectrum (20 keV to 400 keV)
  - ASIM's MMIA instrument (optical camera + photometers)
    - optical emissions?
References

Thank you for your attention

References:

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● Sarria, D., Blelly, P.-L., and Forme, F. (2015)
  MC-PEPTITA: A Monte Carlo model for Photon, Electron and Positron Tracking In Terrestrial
  Atmosphere. Application for a terrestrial gamma ray Flash. JGR (Space Physics)
  - doi: 10.1002/2014JA020695

● Hazelton, B. J., Grefenstette, B. W., Smith, D. M., Dwyer, et al. (2009)
  Spectral dependence of terrestrial gamma-ray Flashes on source distance. Geophys. Res. Lett.
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● The Geant4-based Monte-Carlo code used to propagate TGF and secondary particles in the
  atmosphere is freely available in one of the following repositories:
  ○ https://doi.org/10.5281/zenodo.25970390
  ○ https://github.com/DavidSarria89/TGF-TEB-Propagation-Geant4
e-/e+ motion above 100 km altitude

The magnetic moment $\mu$:

- a.k.a. "the first adiabatic invariant"
- is conserved
- Implies that some electrons can mirror, or get trapped
  -> "magnetic bottle"
e⁻/e⁺ motion above 100 km altitude
**e⁻/e⁺ motion above 100 km altitude**

**ISOTROPIC**

\[ \theta = \text{half cone angle} \]
Lightcurve simulation

- Here, it is assumed:
  - instantaneous TGF source
  - typical bremsstrahlung spectrum
  - production altitude of 15 km (*tested later*)
  - opening angle gaussian with standard deviation of 30 degrees (*tested later*)

- Travel time from production (15 km) to satellite: ~ 2.2 ms
- **TEB response gives a better explanation**, but
  - MXGS probably detected both TEB and parent TGF
  - TEB about 30 times greater flux
  - No mirror pulse

! : photons and electrons are arbitrarily scaled to the same maximum
**Introduction: Terrestrial Electron Beam**

Photons in red, electrons in blue

courtesy J. R. Dwyer

Altitude (km)

- **below 50 km altitude**: collisions dominate, Earth's magnetic field's effect negligible
- **above 100 km altitude**: effect of Earth's magnetic field **must** be included

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e- : - Competition between collision with the atmosphere and magnetic field

- **below 50 km altitude**: collisions dominate, Earth's magnetic field's effect negligible
- **above 100 km altitude**: effect of Earth's magnetic field **must** be included