Recent developments on TGF production models

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Introduction

- Typical max. energy: $\sim 30$ MeV.
- Max. energy reported (AGILE): 100 MeV! [Tavani et al., PRL, 106, 018501, 2011].
- Typical duration: fraction of ms.
- $t_{50}$-duration distribution peak reported between $\sim 100 \mu s$ (Fermi) [Fishman et al., JGR, 116, A07304, 2011] and $\sim 200 \mu s$ (AGILE) [Marisaldi et al., 2014].
- Typical fluence: $\gtrsim 1$ photon/cm$^2$ when observed from low-orbit.
- The maximum TGF fluence is yet to be established (due to deadtime, pile-up, etc.).
Introduction

Illustration of a TGF. Credit: NASA/Goddard Space Flight Center

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Example of a multi-peak TGF detected by AGILE [Marisaldi et al., JGR, 119, 1337, 2014]

What is the origin of these energetic radiation bursts?
Introduction

- TGF spectrum is consistent with bremsstrahlung emission (or “braking radiation”) from energetic electrons.

Bremsstrahlung emission process.

- Production of energetic electrons in the atmosphere?
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Introduction

Relativistic Runaway Electron Avalanches
Stepped leader and energetic radiation
High-energy photon transport
High-energy AGILE anomalous spectrum
Optical emissions associated with TGFs
Outlook

Two theories to explain TGFs

- **RREA in thunderstorm weak electric field** [e.g., *Dwyer*, JGR, 113, D10103, 2008]
- **Thermal runaway electrons in the leader field** [e.g., *Celestin and Pasko*, JGR, 116, A03315, 2011]
Relativistic Runaway Electron Avalanches
seeded by energetic electrons produced by cosmic rays alone

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[\textit{Dwyer et al.}, JGR, D09206, 2010, Figure 1].


- \textit{Dwyer et al.} [JGR, 113, D10103, 2008] demonstrated that TGFs cannot be produced by relativistic runaway electron avalanches acting on natural background radiation or extensive cosmic-ray air showers alone.
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Relativistic Runaway Electron Avalanches
seeded by energetic electrons produced by cosmic rays + relativistic feedback

[Dwyer, Phys. Plasmas, 14, 042901, 2007, Figure 2].

- Relativistic feedback: gamma-rays can create new runaway electrons by Compton scattering, electron-positron pair production, 2nd order feedback from positron’s bremsstrahlung or annihilation.

- Self-propagating relativistic feedback streamer has been suggested to occur for large potential differences [Dwyer, JGR, 117, A02308, 2012; Liu and Dwyer, JGR, 118, 2359, 2013].

- Feedback requires electric fields >4 kV/cm ($\times N/N_0$) extending over several kilometers [e.g., Skeltved et al., JGR, 119, 9174, 2014], while measurements show ambient electric fields <2 kV/cm ($\times N/N_0$) in thunderclouds [e.g., Marshall et al., JGR, 100, 7097, 1995].
Assuming a TGF source at 15 km, the RREA spectra at satellite altitude matches RHESSI averaged TGF spectrum \cite{Dwyer and Smith, GRL, 32, L22804, 2005}. 

\begin{align}
\text{RREA theory} & \sim \exp(-\frac{\mathcal{E}}{7 \text{ MeV}})/\mathcal{E} \\
\end{align}
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Stepped leader propagation

Illustration of the production of thermal runaway electrons and their acceleration in the lightning leader field during the negative corona flash process.
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Electric field produced during the negative corona flash of a stepping leader

Lightning leader
l=1 km, r=1 cm
E_0=0.1 kV/cm
U_l ~ 5 MV

Injection of 65 keV electrons

We use the method of moments [Balanis, 1989] to calculate the charge distribution in the leader channel in a given large-scale electric field E_0.
Electron acceleration in the electric field produced during the negative corona flash of a stepping leader

We use the method of moments [Balanis, 1989] to calculate the charge distribution in the leader channel in a given large-scale electric field \( E_0 \).

Lightning leader
- \( l = 1 \text{ km}, r = 1 \text{ cm} \)
- \( E_0 = 0.1 \text{ kV/cm} \)
- \( U_l \sim 5 \text{ MV} \)
Potential drop in front of the leader tip: $U_l = E_{\text{amb}}L/2$, where $E_{\text{amb}} \approx 0.1\ \text{kV/cm}, 0.1\ \text{kV/cm}, 0.6\ \text{kV/cm}, 0.8\ \text{kV/cm}, \text{ and } 1\ \text{kV/cm}$, and $L \approx 1\ \text{km}, 2\ \text{km}, 2\ \text{km}, 4\ \text{km}, \text{ and } 6\ \text{km}$ are taken to construct potential drops of $5\ \text{MV}, 10\ \text{MV}, 60\ \text{MV}, 160\ \text{MV}, \text{ and } 300\ \text{MV}$, respectively.

The bremsstrahlung emission is simulated using the analytical bremsstrahlung differential cross section $\frac{d\sigma_{\gamma}}{d\varepsilon_{\gamma}}(\varepsilon, \varepsilon_{\gamma})$ from [Heitler, 1954, p. 249].
Monte Carlo model to simulate photon transport
Source altitude determination and comparison to RHESSI measurements

RHESSI data are reproduced from [Dwyer and Smith, GRL, 32, L22804, 2005]. The detector response matrix was taken from http://scipp.ucsc.edu/~dsmith/tgflib_public/data/ [Xu et al., GRL, 39, L08801, 2012]
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Fluence at satellite altitude

- The number of photons reaching satellite altitude (∼500 km) depends mainly on the number of photons at the source, the source altitude, and the source photon spectrum.

- Using the Monte Carlo model of photon transport through the atmosphere, one obtains the predicted TGF fluence at an altitude of 500 km and a radial distance of 200 km from the source:

<table>
<thead>
<tr>
<th>Potential drop</th>
<th>Fluence</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MV</td>
<td>$9 \times 10^{-11}$ ph/cm²</td>
</tr>
<tr>
<td>10 MV</td>
<td>$5 \times 10^{-9}$ ph/cm²</td>
</tr>
<tr>
<td>60 MV</td>
<td>$1.5 \times 10^{-4}$ ph/cm²</td>
</tr>
<tr>
<td>160 MV</td>
<td>0.01 ph/cm²</td>
</tr>
<tr>
<td>300 MV</td>
<td>0.6 ph/cm²</td>
</tr>
</tbody>
</table>

Number of photons with energy $>10$ keV at the source calculated from a reference of $10^{11}$ in a 5 MV leader case [Schaal et al., JGR, 117, D15201, 2012; Xu et al., GRL, 41, 7406, 2014].

⇒ TGFs detected by satellites represent only a small fraction of a much larger distribution [see Østgaard et al., JGR, 117, A03327, 2012].
Non-equilibrium features

Panel (a): Homogeneous electric field 12.5 kV/cm. Panel (b): Inhomogeneous electric field produced by a 350 MV stepping lightning leader.
Non steady state lightning-produced TGF spectrum

Optical emissions associated with TGFs

Illustration of optical emissions produced by two TGF production mechanisms [Xu et al., JGR, 120, 1355, 2015, Figure 1].
Optical emissions associated with TGFs

**Table 2.** Intensity of Optical Emissions from $2PN_2$ (Column 3) and $1NN_2^+$ (Column 4) in Rayleighs and Intensity Ratio Between $2PN_2$ and $1NN_2^+$ (Column 5) in the Visible Range With Wavelengths Between 390 nm and 700 nm for Different Acceleration Processes (Column 1) With Different Characteristic Sizes (Column 2) Calculated at Ground Level

<table>
<thead>
<tr>
<th>Process</th>
<th>Radius (m)</th>
<th>$2PN_2$ (R)</th>
<th>$1NN_2^+$ (R)</th>
<th>$\frac{2PN_2}{1NN_2^+}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>RREA (4.3 kV/cm)</td>
<td>1000</td>
<td>$8.99 \times 10^8$</td>
<td>$1.22 \times 10^9$</td>
<td>0.74</td>
</tr>
<tr>
<td>RREA (12.5 kV/cm)</td>
<td>1000</td>
<td>$1.70 \times 10^9$</td>
<td>$1.55 \times 10^9$</td>
<td>1.10</td>
</tr>
<tr>
<td>RREA (18.8 kV/cm)</td>
<td>1000</td>
<td>$6.63 \times 10^9$</td>
<td>$1.31 \times 10^9$</td>
<td>5.06</td>
</tr>
<tr>
<td>Thermal runaway electrons</td>
<td>50</td>
<td>$8.28 \times 10^{11}$</td>
<td>$5.23 \times 10^{11}$</td>
<td>1.58</td>
</tr>
<tr>
<td>Streamer zone</td>
<td>40</td>
<td>$6.83 \times 10^{10}$</td>
<td>$6.75 \times 10^8$</td>
<td>101.19</td>
</tr>
</tbody>
</table>

[Xu et al., JGR, 120, 1355, 2015, Table 2].
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Two main models can explain TGFs (large-scale RREAs and +IC lightning).

Theoretical predictions on spectra, fluences, optical emissions, radio emissions, time dynamics (lightcurves), and accompanied electrical in-cloud activity, must be used to discriminate between those models.

Need for faster instruments to reduce deadtime and pile-up.

ASIM (ESA) and TARANIS (CNES).

Need for observations at higher energies (up to 100 MeV) to confirm or invalidate AGILE high-energy anomalous spectrum.
Thank you for your attention.

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