Conditions for Production of Terrestrial Gamma Ray Flashes (TGF)

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Terrestrial Gamma Flashes (TGF)

- ~1 ms duration
- Photon energies of up to 20 MeV
- Hard photon spectrum \( \sim E_{ph}^{-1} \)
- 10-100 J total energy (assuming isotropic emission)
- First observed by BATSE, ~1/month
- RHESSI detects ~10-20/month, => ~50/day globally
- Are thought to be produced by bremsstrahlung by ~35 MeV electrons at >30 km altitudes [Smith et al., 2005]
Burst and Transient Source Experiment

- Was located on CGRO (Compton Gamma Ray Observatory)
- In orbit Apr 5, 1991 – June 4, 2000
- 450 km altitude
- 28.5° inclination
- 20 keV - 1.9 MeV photons
- ~2000-10000 cm² effective area
BATSE TGFs
[Fishman et al 1994]
Equatorial observation of TGF by BATSE

TGFs occur in regions with high lightning activity
RHESSI

- Reuven Ramaty High Energy Solar Spectroscopic Imager
- Launched on Feb 5, 2002
- Altitude 600 km
- 38° inclination
- 3 keV – 17 MeV photons
- \(~10-100 \text{ cm}^2\) effective area
RHESSI TGFs [Smith et al, 2005]

Lightcurves (4 events)

Scatter plot (1 event)
Spectrum [Smith et al., 2005]

- Black: average measured spectrum
- Red: isotropic bremsstrahlung spectrum (35 MeV electrons)
- Blue: bremsstrahlung with instrumental response
Equatorial observation of TGFs by RHESSI

Color shows lightning activity
Gamma rays are produced by bremsstrahlung from relativistic runaway electrons (RRE)

RRE are accelerated by:
  - Electro-magnetic pulse from lightning (EMP) – suggested by equatorial observations of TGFs
  - Quasi-electrostatic (QES) field
General results of relativistic runaway electron (RRE) avalanche theory (Monte Carlo simulations)
Relativistic Runaway Mechanism and Dynamic Friction Force

43 inelastic processes:
- Rotational, vibrational and electronic excitations
- Dissociative losses
- Ionization

\[
F = \sum N\sigma_i(v)\Delta\varepsilon_i
\]

In townsend (1 Td = 10^{-21} \text{ V-m}^2):

\[
E/N = 8 \text{ Td, } 130 \text{ Td, } 1000 \text{ Td}
\]
Relativistic Runaway Electron Avalanche

- Cosmic ray primaries
- Ionization with production of relativistic electrons
- Acceleration

Electron thermalizes due to collisions

Cosmic ray shower

Cosmic rays produce $\sim 10^{-5}/\text{cm}^3\cdot\text{sec}$

$>1$ MeV electrons at $\sim 10$ km altitude
Monte Carlo simulations

Method:

- Relativistic motion
  \[ \frac{dp}{dt} = -eE - \frac{e}{m\gamma} p \times B + G(t) \]

- \( G(t) \) includes continuous and discontinuous inelastic energy losses and elastic scattering

- New electrons from ionization

Results:

- Electron distributions
- Avalanche growth rate: \( N = N_0 e^{Rt} \)
- Drift velocity
The exponential time growth rate $R$ of the avalanche

- No magnetic field:

$$R = 2\pi N_m Z_m r_0^2 c \left( (\delta - 1) + 0.04(\delta - 1)^2 \right), \quad \delta = E / E_t$$

- The rate decreases slowly with increasing $B$ at small $B$

- The avalanche is quenched approximately when $B > 2E/c$
RRE magnetization altitude (at the geomagnetic equator)

- For $f_{H0} = 1$ MHz
- Elastic: $\nu_m = \omega_H$ ($\nu_m$ is the momentum transfer rate)
- Inelastic: $F_D/p = \omega_H$ ($F_D$ is the dynamic friction)
Conditions on Quasi-Electrostatic Field: Dependence of the post-discharge field on the ambient conductivity profile
- Electrons are avalanching in a QES E field following a +CG discharge
- High discharge values and high altitudes of the removed charge are required
- Electron motion at >35km altitude is determined by geomagnetic field $B_E$
- If $B_E$ is non-horizontal, the electrons are predicted to leave the atmosphere.
Quasi-Electrostatic Field

BEFORE DISCHARGE

E (small)

negative screening charge

10 km
5 km

+ Q
- Q

1 ms

AFTER DISCHARGE

Large E causes runaway breakdown

negative screening charge

10 km
5 km

- Q
Post-discharge electric field

- Exceeds relativistic runaway threshold
- Accelerates electrons upward
- In atmosphere with exponential conductivity profile:

\[ \Phi_{\text{disch}} = \frac{Q}{4\pi\varepsilon_0} \exp\left[\frac{-(r + z)}{2H}\right] - 1 \]
Fluid model of RRE avalanche (stationary case)

\[ \nu \frac{dN}{dz} = RN + S \]

- **Notations:**
  - \( \nu \approx 0.9c \) – drift velocity
  - \( R(\delta=E/E_t) \sim N_m \) – avalanche rate
  - \( S \sim N_m \) – source from cosmic rays, =10 m\(^{-3}\) s\(^{-1}\) at 10 km

- **Avalanche rate (\( \delta=E/E_t \))**
  \[ R = 2\pi N_m Z_m r_0^2 c \left( (\delta - 1) + 0.04(\delta - 1)^2 \right) \]

- **At geomagnetic equator (\( E \perp B \)), \( R=0 \) when \( cB/E_t > 2 \)**
Gamma photon production
[as in Inan and Lehtinen, 2005]

\[ \frac{dN_{ph}}{dt} = \int \chi v NN_m dV \]

- \( \chi \approx 10^{-28} \text{ m}^2 \) is the bremsstrahlung cross-section by 35 MeV electrons in RHESSI energy interval 3 keV-17 MeV
- Transverse area of the beam \( A \sim (10 \text{ km})^2 \) [Lehtinen et al., 1997]
- Duration \( \Delta t \sim 0.1 \text{ms} \)

=>

\[ N_{ph} = A \Delta t \int \chi v NN_m dz \]
Atmosphere conductivity: the crucial factor

- We study the dependence of E field on ambient conductivity distribution
- Decrease of conductivity in the cloud (<20 km) can be due to ion absorption by water droplets
Post-discharge E field (various conductivity profiles)

- Smaller conductivity scale leads to greater field
- The sharp conductivity drop leads to greater field due to the screening charge accumulation in a thin layer on the cloud top

+CG from 18 km [Gurevich et al, 2001]

Q=100 C
Runaway electrons and Gamma Photons: Vertical B

- Assume +CG discharge from 18 km [Gurevich et al, 2001]
- The observed photon number is $\sim 3 \times 10^{15}$ [Smith et al, 2005], corresponding to the upper boundary of the right panel
- The required charge varies from $\sim 175$ to $\sim 450$ C, depending on the ambient conductivity profile

![Graph of Vertical B](attachment:image.png)

![Graph of Photon number with vertical B](attachment:image.png)
Runaway electrons and Gamma Photons: Horizontal B

- The avalanche stops at 30-45 km
- The required charge is greater than for vertical B and varies from ~200 to >500 C, depending on the ambient conductivity profile
Electromagnetic pulse (EMP) mechanism of TGF production
Features of the EMP model vs QES model

Return-stroke EMP:
- Can produce TGFs at the geomagnetic equator
- Runaway electrons do not escape

Quasi-electrostatic (QES)
- Cannot produce TGFs at the geomagnetic equator
- Runaway electrons are predicted to escape to ionosphere
EMP field [Krider, 1992]

\[ E(t) = \frac{\mu_0 I(t - R / c)}{2\pi R} \frac{c \beta \sin \theta}{1 - \beta^2 \cos^2 \theta} \]
The production of TGFs

The optimal angle gives partial synchronization

\[ N_0 = 10^7 \text{ cosmic-ray electrons} \]
Conclusions

- The number of relativistic electrons produced in the avalanche, and therefore, TGF production, depends very nonlinearly on the electric field.
- As a consequence, it depends very sensitively on the ambient conductivity of the atmosphere, which determines the post-discharge quasi-electrostatic field.
- In the case of TGF production by electromagnetic mechanism, the TGF intensity depends very nonlinearly on the current values in the return stroke.