Terrestrial Gamma-Ray Flashes

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TGFs are intense and very brief bursts of energy whose observed geographical distribution peaks in tropical regions [1–8]. Early models associating TGFs with upper atmosphere phenomena ("sprites") or other high-altitude (>30 km) phenomena [9] have now been superseded by models placing TGFs in the altitude range of 10-20 km above sea level [5, 6, 10, 11]. TGFs tend to occur deep in the atmosphere near the upper regions of thunderclouds, as recently confirmed in events associated with intra-cloud discharges propagating upward from the main negative charge centers in high cloud electric fields [10, 11].

About a thousand TGFs have been detected by low-Earth orbiting satellites equipped with instruments sensitive in the MeV energy range (BATSE-GRO [1], RHESSI [2], AGILE [3] and GBM-Fermi [4]). The total TGF radiated energy [2] above 100 keV is E_{TGF} = 20-40 kJ, and typical spectral data obtained by RHESSI can be described [2, 5, 7, 12] by a power-law Bremsstrahlung model of relativistic electrons with a cutoff photon energy of $E_{\gamma c} \sim 10$ MeV. The TGF rate is estimated to be in the range of $10^2 - 10^3$ per day depending on flux intensity, geometry, and model assumptions [2].

There is today a broad consensus for TGF modelling on the relevance of the runaway electron acceleration by very strong electric fields in thunderstorm discharges. TGF models based on the relativistic runaway electron avalanche (RREA) process [5, 12, 13, 18, 21–23] produce a typical electron energy spectrum close to exponential with an e-folding energy scale $E_c \sim 7$ MeV over one avalanche length (∼100 m for typical conditions [12]). A power-law spectrum with an exponential cutoff near 7 MeV is expected with characteristics that are quite independent of the conditions (seed electrons, local electric fields, altitudes) [5, 12, 13].

Recent results by the AGILE satellite challenge this picture. A significant number of TGFs is indeed detected at photon energies reaching 100 MeV with no exponential attenuation [14]. The AGILE data show the existence of a high-energy spectral component in addition to the power-law component extending up to ∼ 10 MeV. The additional component constitutes ∼10% of the total emitted energy. A broken PL fit of the two components gives a differential photon energy flux $F(E) \sim E^{-0.5\pm0.1}$ for 1 MeV $<E<$ E_c, and $F(E) \sim E^{-2.7\pm0.1}$ for $E_c < E < 100$ MeV, with $E_c = (7.1 \pm 0.5)$ MeV [14].

Substantial TGF emission above 10 MeV is confirmed by the AGILE gamma-ray imager Tracker detections of several individual TGF events in the energy range 30-100 MeV [15]. The AGILE Tracker detections provide indeed the first precise TGF imaging from space, and agree with the more systematic results reported here that determine the spectrum in the energy range up to 100 MeV.

These results are quite interesting. Maximum cloud-to ground (CG) and intra-cloud (IC) voltage drops have been measured [16, 17] within thunderstorms to be near 100 MV over distances of ∼ 4-6 km. The electric field can locally reach values near E = 50-100 kV/m and above [16, 17] and may temporarily exceed the relativistic runaway breakdown [19] threshold (corresponding to $E_{th} \sim 280$ kV/m at sea level [13, 20]) believed to be necessary to initiate lightning and TGFs. So far, intra-cloud voltage drops, ΔV_{IC}, have been measured in a wide range from several tens to about 100 MV (e.g., ref. [16]). The AGILE measurements show that $\Delta V_{IC} = 100$ MV is a lower limit of the IC potential drop for the most extreme events. Since the electric field is expected to be saturated near values a few times the local runaway breakdown threshold [20], the particle acceleration process is required to be efficiently maintained over macroscopic lengths comparable with cloud sizes or intra-cloud distances.

Relativistic electron TGF models [5, 13, 22, 23] involve a typical total electron number $N_e \sim 10^{17}$ for an exponentially cutoff photon spectrum of average photon energy of a few MeV. The AGILE results strengthen even more this conclusions, adding an additional power-law component of primary particles (electrons and possibly positrons) reaching kinetic energies of hundreds of MeV. These primary particles radiate gamma-rays by Bremsstrahlung, and the secondary photons Compton scatter and produce electron/positron pairs as they propagate in the atmosphere. In addition to these processes, an important reaction is induced by gamma-rays in the energy range 10-100 MeV, i.e., the photo-production of neutrons from gamma-rays interacting with atmospheric nitrogen and oxygen (e.g., refs. [24–26]). The photo-production cross sections for N and O have a threshold above 10 MeV and peak just near 20-30 MeV. These results are then crucial for a correct evaluation of the TGF photo-neutron production: the high-energy tail above 10 MeV turns out to be *not* a small fraction (close to 1% as considered, e.g., in ref. [26]) but rather amounts to about 10% of the total energy. We deduce a typical TGF neutron yield $N_n \geq 10^{13}$, that is larger by at least one order of magnitude compared to previously calculated values (e.g., [26]). Gamma-rays up to about 10 MeV have been detected also on the ground in conjunction with atmospheric discharges or thunderstorms (e.g., [27–30]), and neutrons have been searched and detected on the ground in temporal coincidence with lightning [31–33]. The high-energy TGF spectrum constitutes a crucial input for future detailed calculations of the photon/neutron production and atmospheric radiation transfer.

Terrestrial Gamma-Ray Flashes turn out to be very efficient particle accelerators in our atmosphere. Future observational and theoretical investigations of these issues are necessary to fully analyze the TGF phenomenon and its consequences.

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