Terrestrial Gamma-Ray Flashes as Powerful Particle Accelerators

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(Received 16 September 2010; published 3 January 2011)

Strong electric discharges associated with thunderstorms can produce terrestrial gamma-ray flashes (TGFs), i.e., intense bursts of x rays and γ rays lasting a few milliseconds or less. We present in this Letter new TGF timing and spectral data based on the observations of the Italian Space Agency AGILE satellite. We determine that the TGF emission above 10 MeV has a significant power-law spectral component reaching energies up to 100 MeV. These results challenge TGF theoretical models based on runaway electron acceleration. The TGF discharge electric field accelerates particles over the large distances for which maximal voltages of hundreds of megavolts can be established. The combination of huge potentials and large electric fields in TGFs can efficiently accelerate particles in large numbers, and we reconsider here the photon spectrum and the neutron production by photonuclear reactions in the atmosphere.

DOI: 10.1103/PhysRevLett.106.018501 PACS numbers: 92.60.hx, 52.59.Dk, 52.80.Mg

Introduction.—Terrestrial gamma-ray flashes (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 30 km) phenomena [9] have now been superseded by models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 intracloud 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 $E_{\rm TGF} = 20$–40 kJ, and the pre-AGILE spectral data can be described [2,5,7,12] by a power-law (PL) 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].

In this Letter, we report the results of a systematic study of the TGF high-energy emission with space data obtained by the AGILE mission that has been operational since April 2007. The AGILE instrument is equipped with two detectors [Mini-Calorimeter (MCAL) and γ-ray tracker, see below] that are capable of detecting impulsive events and TGFs, in particular, with high efficiency for photon energies above a few tens of MeV. Current theoretical models of TGF high-energy emission based on relativistic runaway avalanche calculations [5,12,13] have specific spectral predictions in the high-energy range. A power-law spectrum with an exponential cutoff near 10 MeV is expected with characteristics that are quite independent of the conditions (seed electrons, local electric fields, altitudes) [5,12,13].

AGILE observations.—The AGILE space mission [14] of the Italian Space Agency (ASI) is characterized by a very compact instrument sensitive in the energy range from several tens of keV to several GeV, with excellent timing capabilities. In this Letter we focus, in particular, on the data obtained by the (nonimaging) MCAL detector [15] that can detect impulsive events in the energy range 350 keV–100 MeV using a special submillisecond trigger logic [16]. The instrument is equipped with a γ-ray tracker sensitive in the range 30 MeV–30 GeV [17] and a hard-x-ray detector sensitive in the range 18–60 keV [18]. Both the tracker and super-AGILE are imaging detectors devoted to the study of astrophysical sources and with an operational mode that is not optimized for Earth observations. On the other hand, the MCAL detector can reveal impulsive events from all directions with very good efficiency because of an appropriate on-board event selection and trigger. Millisecond flash candidates are then triggered by MCAL on board and transmitted to the ground for background filtering. It turns out that cosmic and terrestrial impulsive MCAL events can be distinguished by their spectral hardness. TGFs are usually detected with relatively large values (larger than 0.5) of the hardness ratio defined as $R_H = (\text{counts with } E > 1.4 \text{ MeV})/(\text{counts with } E < 1.4 \text{ MeV})$.

The AGILE satellite is ideally suited for TGF detection for several reasons: (1) the satellite orbit is equatorial (inclination angle of 2.5°) with a low particle background; (2) the MCAL on-board data acquisition is based on a submillisecond trigger logic; (3) the MCAL energy range (0.35–100 MeV) permits sampling of the largest emitted photon energies (and therefore the largest TGF particle accelerating potentials); (4) the mission ground segment is very efficient [19,20] using the ASI station in Malindi (Kenya) and the data processing at the ASI Science Data Center and Team sites. Since its launch in April 2007, AGILE has been detecting TGFs with high efficiency. Figure 1 shows the light curves, photon energy distributions, and energy spectra for three intense TGFs detected by AGILE with photons detected above 40 MeV. An average spectral model derived later in this section is normalized to the individual TGF data and superimposed to the counts spectra. The average model matches the data well, although the limited counting statistics does not allow us to constrain different models for individual TGF data, especially at high energy.

Based on the MCAL trigger selection capability and energy range, we focused on the spectral properties of TGFs at the highest detectable energies. MCAL is fully calibrated in the energy range 0.35–100 MeV for a 4π acceptance. The MCAL detector response for different off-axis angles has been derived by a combination of simulations and calibration data obtained up to a few MeV with radioactive sources, and up to 460 MeV at the beam test facility of the National Laboratories of Frascati (Italy). The MCAL energy resolution turns out to be ~10% for photon energies above 10 MeV. In-orbit calibration consistency checks were obtained for different γ-ray bursts at different angles. A cumulative TGF spectrum has been obtained for the 130 events satisfying stringent TGF selection criteria detected during the period June 2008–January 2010. The relevant cumulative background as a function of energy is calculated for events detected in the time interval $T_0 + 1 \text{ sec} - T_0 + 21 \text{ sec}$, where T_0 is the TGF start time. This method takes into account the 20% orbital modulation of the MCAL background in a satisfactory way. We note that the MCAL background level on TGF time scales is quite low (because of the MCAL anticoincidence vetoing and of the satellite equatorial orbit), being 0.35 events per ms on average.

Figure 2 shows the background-subtracted cumulative energy spectrum of our TGF sample. Remarkably, we find that the TGF spectrum extends up to 100 MeV with no exponential attenuation. Our data show the existence of a high-energy spectral component in addition to the well-known PL 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 $1 \text{ MeV} < E < E_c$, and $F(E) \sim E^{-2.7\pm0.1}$ for

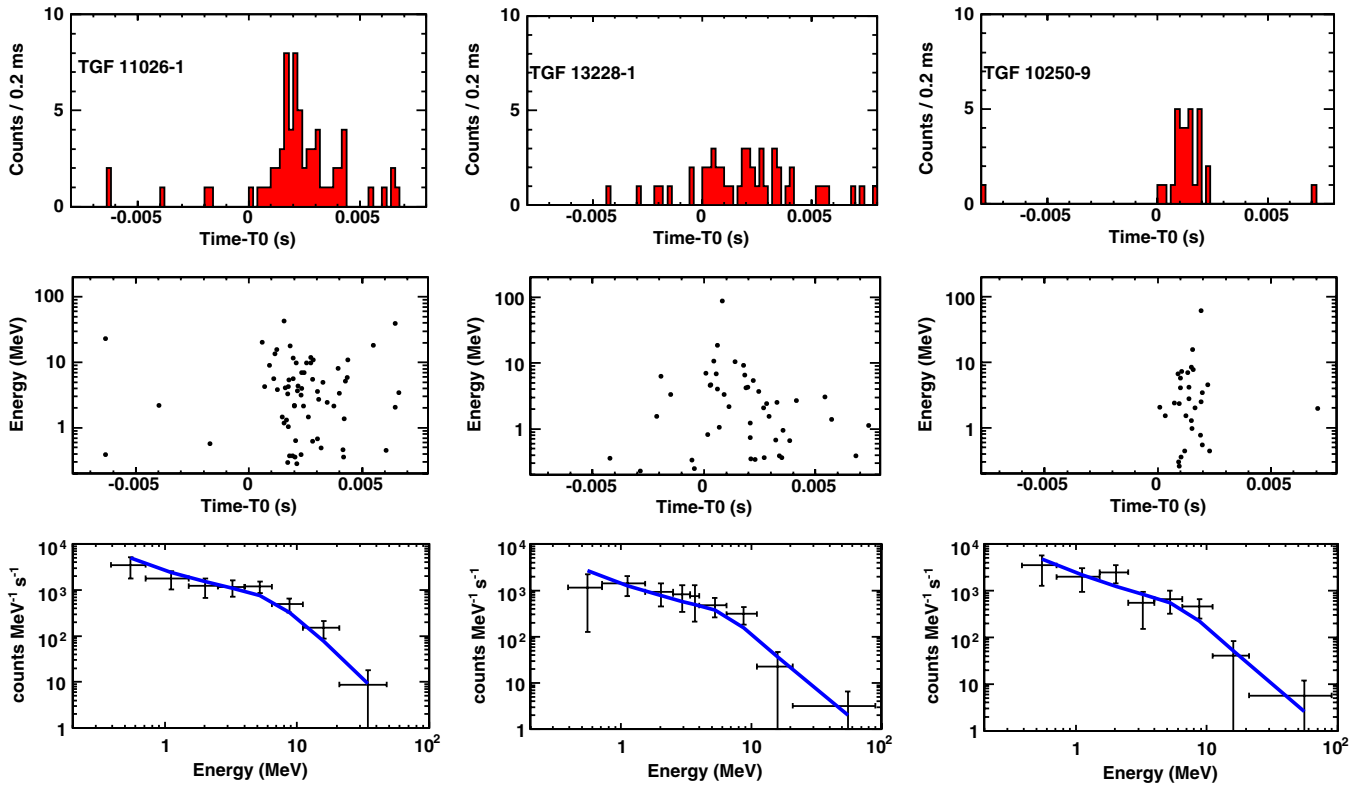

FIG. 1 (color online). Light curves, photon energy distributions, and spectra of three intense TGFs detected by AGILE. (Top panels) AGILE-MCAL light curve for events above 350 keV with 0.2 ms time bins. The trigger time is marked as T_0. (Middle panels) Photon energy distributions as a function of arrival times. (Bottom panels) MCAL counts spectrum as a function of photon energies: the solid blue curve shows the normalized cumulative spectrum (the same as in Fig. 2) obtained by summing 130 high-quality TGFs detected by AGILE during the period June 2008–January 2010.

$E_c < E < 100$ MeV, with $E_c = (7.1 \pm 0.5)$ MeV (all quoted parameter errors are 1σ). We notice that the MCAL determination of substantial TGF emission above 10 MeV is confirmed by the AGILE γ-ray imager tracker detections of several individual TGF events in the energy range 30–100 MeV [21]. 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. We also note that among a total of 130 TGFs, the 8 TGFs with tracker detections discussed in [21] turn out to be different from the 14 TGFs which exhibit at least one MCAL photon with $E > 40$ MeV. Given the current statistics, we cannot determine whether the geographical or temporal distributions of TGFs detected above 40 MeV are different from the total sample.

Discussion.—Considering the bremsstrahlung photon energy conversion efficiency and atmospheric attenuation effects, TGFs make use of particle acceleration of electric voltages near the maximum values that can be established between thunderstorm discharge sites. Indeed, maximum cloud-to ground and intracloud (IC) voltage drops have been measured [22,23] 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 [22,23] and may temporarily exceed the relativistic runaway breakdown [24] threshold (corresponding to $E_{\rm th} \sim 280$ kV/m at sea level [13,25]) believed to be necessary to initiate lightning and TGFs. So far, intracloud voltage drops $\Delta V_{\rm IC}$ have been measured in a wide range from several tens to about 100 MV (e.g., Ref. [22]). Our measurements show that $\Delta V_{\rm IC} = 100$ 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 [25], the particle acceleration process is required to be efficiently maintained over macroscopic lengths comparable with cloud sizes or intracloud distances.

Our results are very important for a theoretical modeling of the TGF phenomenon. There is today a broad consensus for TGF modeling 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 [5,12,13,26–29] 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]). This result is almost independent of ambient conditions, gas density, electric field strengths, or details of the seed population (e.g., Refs. [5,13]). The spectral results reported

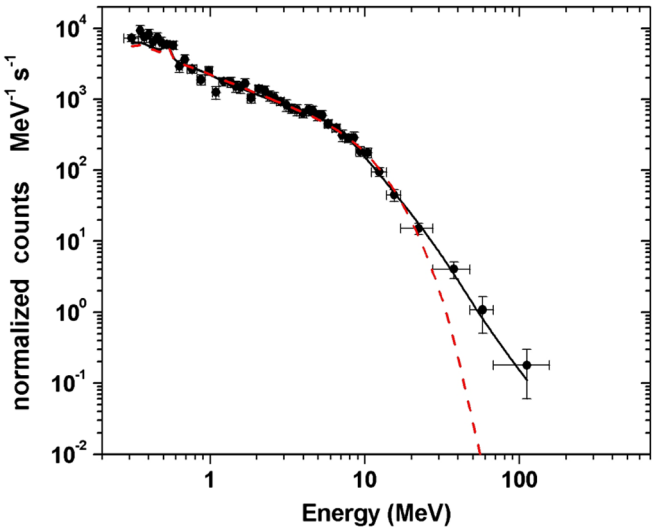

FIG. 2 (color online). The background-subtracted cumulative counts spectrum of the 130 TGFs detected by AGILE-MCAL during the period June 2008–January 2010. The solid curve shows the broken PL fit (see text), and the dashed curve is a pre-AGILE phenomenological model $F(E) \sim E^{-\alpha} e^{(-E/E_c)}$, of index $\alpha = 0.4 \pm 0.2$ and exponential cutoff energy $E_c = 6.6 \pm 1.2$ MeV.

here are difficult to reconcile with current models. To explain the observed photon energies, RREA models imply particle acceleration over distances corresponding to many avalanche multiplication lengths. It remains then to be determined whether this is possible without contradicting the limits on the avalanche multiplication factor [13,25] and without a substantial revision of the TGF underlying physical processes.

We note that in principle a superposition of power-law distributions with different cutoff energies E_c's can mimic a broken power-law spectrum. However, in our case we find that the cutoff energies should span a large energy range (3–5 or more) to account for the observed high-energy tail. In current models E_c is closely related to the average electron energy gained during the RREA process, and a broad distribution of E_c's would lead us to consider alternative theoretical scenarios. The current limited statistics above 10 MeV does not allow one to study the spectral variability of individual TGFs at high energies. Since the MCAL effective area at high energy is comparable or larger than that of currently operating TGF-detecting experiments, the observation of high-energy spectral variability requires a new class of space detectors.

Relativistic electron TGF models [5,13,28,29] 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. Our results strengthen this conclusion even more, adding an additional power-law component of primary particles (electrons and possibly positrons) reaching kinetic energies of hundreds of MeV. These primary particles radiate γ 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 γ rays in the energy range 10–100 MeV, i.e., the photoproduction of neutrons from γ rays interacting with atmospheric nitrogen and oxygen (e.g., Refs. [30–32]). The photoproduction cross sections for N and O have a threshold above 10 MeV and peak just near 20–30 MeV. Our results are then crucial for a correct evaluation of the TGF photoneutron 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. [32]), 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 1 order of magnitude compared to the previously calculated value [32]. γ rays up to about 10 MeV have been detected on the ground in conjunction with atmospheric discharges or thunderstorms (e.g., [33–36]), and neutrons have been searched and detected on the ground in temporal coincidence with lightning [37,38]. The TGF spectrum of Fig. 2 constitutes a crucial input for a detailed calculation of the photon-neutron production and atmospheric radiation transfer aimed to explain these observations.

Conclusions.—Terrestrial gamma-ray flashes turn out to be very efficient particle accelerators in our atmosphere. Our detected power-law emission between 10 and 100 MeV is difficult to reconcile with current RREA models [5,12,13,26–29]. Some of these models are characterized by acceleration over typical distances near, e.g., stepped-leader lightning sizes ($\sim$ 50–100 m) that correspond to a small number of avalanche lengths. On the contrary, an observed photon energy of 100 MeV implies a lower limit on the acceleration distance $d_{\min} \simeq (1\ \mathrm{km}) \times (\bar{E}_{100})^{-1}$, where $\bar{E}_{100}$ is the average electric field in units of 100 kV/m. These large-scale sizes are a significant fraction of the intracloud or cloud-to-ground distances over which potential drops of order of 100 MV can be established in thunderstorms. Furthermore, the detection of TGF emission in the 10–100 MeV range renews the interest for the neutron production in these energetic events as well as in normal lightning. Future theoretical investigations of these issues are necessary to fully analyze the TGF phenomenon and its consequences.

AGILE is an Italian Space Agency (ASI) mission with scientific and programmatic contributions by the Italian Institute of Astrophysics (INAF) and the Italian Institute of Nuclear Physics (INFN). Research partially funded through the ASI Contract No. I/089/06/2. We acknowledge extensive discussions with the ASI and INAF Directorates, and useful exchanges with F. Prodi, A. Mugnai, and E. Arnone.

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