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A terrestrial gamma-ray flash recorded at the Lightning Observatory in Gainesville, Florida

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ABSTRACT

A terrestrial gamma-ray flash (TGF) observed at ground level is presented. It was recorded at the Lightning Observatory in Gainesville, Florida, on June 13, 2014. Ground-based observations of TGFs are very rare. To date, only two positively identified ones are found in the literature. Our TGF was associated with a single-stroke negative cloud-to-ground discharge. It had a duration of 16 μs and consisted of 6 pulses, two of which exceeded the upper measurement limit of 5.7 MeV. The pulses apparently corresponded to individual photons, which is a characteristic feature of TGFs. The TGF began 191 μs after the return-stroke electric field peak. The stepped leader duration was as short as 3.9 ms. There was essentially no energetic radiation detected during the leader process. The NLDN-reported return-stroke peak current was as high as 224 kA. The characteristics and occurrence context of the LOG-recorded TGF are compared to those of the two similar events found in the literature. In all three cases there was evidence of a channel carrying appreciable current to ground at the time of TGF, and the associated (preceding or concurrent) cloud-to-ground discharge processes were unusually intense.

1. Introduction and literature review

Recent observations of hard x-rays and gamma-rays in thunderstorms (other than the enhancements of gamma-ray background due to precipitation of radon by rain) fall into three categories: surges in the gamma-ray background (gamma-ray glows) lasting seconds to minutes; bursts of x-rays associated with all kinds of natural and triggered lightning leaders, typically occurring within less than 1 ms of the return stroke; and Terrestrial Gamma-ray Flashes or TGFs (typically less than 1 ms in duration). The latter are usually observed from space, but on a few occasions were seen on the ground or from an aircraft. At present, the only viable mechanism for producing energetic radiation by lightning and thunderstorms involves runaway electrons, which occur when the energy gained by the free electrons between collisions, as they are accelerated by high electric field, exceeds the energy that is lost by collisions with air molecules. X-rays and gamma-rays are produced via what is called bremsstrahlung (braking radiation) that is emitted when a free electron is deflected in the electric field of a nucleus or, to a lesser extent, in the field of an atomic electron.

The energy spectrum of observed gamma-ray glows is consistent with the relativistic runaway electron avalanche (RREA) mechanism (also referred to as the relativistic runaway breakdown theory), which requires energetic (of the order of 0.1–1 MeV) seed electrons produced by cosmic rays and sufficiently high electric fields (calculated to be of the order of 100 kV/m at an altitude of 6 km) extending over a sufficient distance (of the order of a kilometer). For all types of negative lightning leaders, the energy of individual x-ray photons was estimated to be in the 30–250 keV range (the upper limit is twice the energy of a chest x-ray), although occasionally photons in the MeV range were observed. It is likely that x-ray emissions from cloud-to-ground lightning leaders are associated with the so-called cold runaway (also known as thermal runaway) breakdown, in which very strong electric fields (>30 MV/m) cause the higher-energy tail of the bulk free electron population to grow, allowing some electrons to runaway to high energies. Such very high fields may be present at streamer heads or leader tips. It does not appear that runaway electron production is a necessary feature of lightning leaders. TGFs are associated with thunderstorms and individual lightning flashes, with accompanying electromagnetic signals (sferics) mostly suggesting intracloud flashes effectively transporting negative charge upward, including some compact intracloud discharges (CIDs), as the type of parent lightning.

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All three TGFs reported from ground-based observations (including the one presented in this paper) occurred in Florida and were associated with cloud-to-ground discharges effectively transporting negative charge to ground. It is worth noting that we do not consider here x-ray/gamma-ray observations at ground level reported by Ringuette et al. (2013, 2014), because some or all of their events (all labeled as TGFs) could be associated with leaders near ground, such events being outside the scope of this study. It is thought that TGFs are produced by in-cloud lightning processes, but it is not clear what the production mechanism is. One possibility is the cold runaway breakdown during the stepping process of a negative in-cloud leader. On the other hand, according to Dwyer and Cummer (2013), TGFs could be produced in the absence of ordinary lightning, via runaway breakdown processes alone. Since the latter processes emit little visible light, the phenomenon was referred to as dark lightning. Two TGF production mechanisms, RREAs in the large-scale homogeneous electric field inside the cloud and the acceleration of cold runaway electrons in the highly nonuniform electric field of in-cloud leader, are illustrated in Fig. 1 of Xu et al. (2015). Additional information on energetic radiation from lightning is found in Dwyer et al. (2012b).

In this paper, we present the first TGF observed at the Lightning Observatory in Gainesville (LOG), Florida. It was identified using the following criteria: (a) no sign of pile-up, characteristic of x-rays associated with leaders near ground, is seen in the recorded pulses, (b) the duration of the recorded pulse sequence is less than 1 ms, and (c) energy values for the largest pulses corresponding to individual photons exceed 1 MeV. The characteristics and occurrence context of the LOG-recorded TGF are compared to those of the two similar events found in the literature. In order to make this comparison self-contained, we include a number of figures from the previous works.

2. Experimental setup

The Lightning Observatory in Gainesville (LOG) was established on the University of Florida campus in 2004 primarily for measuring electromagnetic fields produced by lightning. Overviews of results obtained at LOG are found in Rakov et al. (2014, 2015). Over the years the experimental setup has undergone upgrades, modifications, expansions, and relocation. It is currently located on the roof of the five-story New Engineering Building (29°38′32″N 82°20′50″W). The LOG includes a glass cupola providing over a 180° unobstructed view of the horizon. The cupola houses digitizing oscilloscopes, computers, and high-speed video cameras, with the various sensors and associated electronics being located nearby on the roof. The sensors currently include electric field antennas, electric field derivative ($\mathrm{d}E/\mathrm{d}t$) antennas, magnetic field derivative ($\mathrm{d}B/\mathrm{d}t$) antennas, and an x-ray detector. The low-gain and high-gain wideband electric field measuring systems have useful frequency bandwidths of 16 Hz–10 MHz and of 360 Hz–10 MHz, respectively. The corresponding decay time constants are 10 ms and 440 μs. The upper frequency response of the $\mathrm{d}E/\mathrm{d}t$ measurement system is 10 MHz. Signals from all the sensors are relayed by fiber-optic links to the glass cupola, where they are recorded and GPS-time stamped. A detailed description of LOG is given by Mallick et al. (2014b).

The TGF record presented here was obtained using the LOG x-ray detector that was previously used in the study of Mallick et al. (2012). The detector consisted of a 7.6-cm length and 7.6-cm diameter cylindrical NaI scintillator coupled with a photomultiplier tube and was powered by a 12-V battery. A 0.32-cm thick aluminum box shielded the detector from moisture and light, but allowed x-rays with energies down to 30 keV to enter from all direction. The output signal of the x-ray detector was transmitted via an analog fiber optic link, Opticomm FM, to an oscilloscope, sampling at 100 MHz.

We used a Cs-137 radioactive source (emitting 662 keV photons) to calibrate the x-ray detector. The upper measurement limit was about 5.7 MeV with the lowest measurable energy being 75 keV. The expected occurrence of background x-rays at LOG is 1 in 8 ms. Additional details about the x-ray detector and background x-ray radiation at LOG can be found in Mallick et al. (2012, 2014a).

LOG data to be presented here include electric field and electric field derivative records corresponding to the observed gamma-ray emission. Unfortunately, no optical data are available for this event (it was outside of the fields of view of high-speed video cameras installed at LOG).

We additionally used data from the US National Lightning Detection Network (NLDN), from the Earth Networks Total Lightning Network (ENTLN), and from the National Weather Service radar located near Jacksonville, FL, 112 km from the LOG.

3. Data presentation

On June 13, 2014, at about 15:53 (UT), a cell in a large (hundred kilometers in extent) thunderstorm system, moving from West to East, passed over Gainesville, Florida. Since its arrival until about 16:20 (UT), the thunderstorm cell, whose 18-dBZ echo top height was approximately 12 km, produced numerous lightning discharges in the Gainesville area. During this time period, the maximum horizontal extent of the cell at an altitude of 5 km above ground increased from 14 to 28 km. The TGF was associated with a negative single-stroke flash that occurred at 16:12:59 (UT) and terminated, according to the NLDN, at a distance of 7.5 km from the LOG. The NLDN also reported one pulse of the preliminary breakdown (PB) pulse train, which was located at a horizontal distance of 3 km from the return stroke, in the high-reflectivity (>45 dBZ) region of the cell, at altitudes of 3–6 km above ground. The stroke to ground and PB pulse were detected by 20 and 3 NLDN sensors, respectively. It follows from the LOG electric field record that the return stroke was followed by a 20-ms duration continuing current. The negative return stroke was also reported by the ENTLN (detected by 527 sensors), GLD360 (detected by 9 sensors), and the LF magnetic field sensor at Duke University at a distance of about 760 km, but was missed by the World Wide Lightning Location Network (WWLLN).

The electric field of the beginning of the PB stage of the TGF-producing flash is shown in Fig. 1. The first discernible PB pulse is marked in the lower panel in Fig. 1, with no pulses exceeding twice the noise level being observed prior to that pulse. The first PB pulse preceded the return stroke by 3.9 ms, which means that the stepped leader duration was very short. There are three possible explanations of that: the leader was very fast, or the main negative charge region was at unusually low altitude, or both. Zhu et al. (2014) found that such short-duration stepped leaders in Florida originated at normal altitudes and, hence, were unusually fast. The following return stroke currents in their study were very high, which is in line with the peak current (224 kA) reported by the NLDN for our event. One of the preliminary breakdown pulses was misclassified by the NLDN as a 50-kA positive return stroke (+CG), located at a horizontal distance of 3 km from the negative-stroke ground termination point.

The magnetic field at 441 km and electric field at 28 km of the TGF-producing stroke recorded by the NLDN and ENTLN, respectively are presented, as examples, in Fig. 2. Also shown in Fig. 2 is the low-gain electric field record obtained at LOG. Not counting the LOG waveforms, the ENTLN waveform is the closest of all the available waveforms for this event. It shows the preliminary