Simultaneous space-based observations of terrestrial gamma-ray flashes and lightning optical emissions: Investigation of the terrestrial gamma-ray flash production mechanisms

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The relative timing between terrestrial gamma-ray flashes (TGFs) and lightning optical emissions is a critical parameter that may elucidate the production mechanism(s) of TGFs. In this work, we study the correlation between optical emissions detected by the Geostationary Lightning Mapper and TGFs triggered by the *Fermi* Gamma-ray Burst Monitor. The correlation result suggests that TGFs are produced during the last stage of lightning leader channel development. Accordingly, TGFs are initiated by lightning leaders perhaps augmented by additional electron acceleration and multiplication by the ambient large-scale electric field in thunderclouds.

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I. INTRODUCTION

Terrestrial gamma-ray flashes (TGFs) are pulses of energetic photons which are intense and brief, originating in the atmosphere during thunderstorm activity. They were first discovered by the Burst and Transient Source Experiment (BATSE) in 1994 [1]. The observations of TGFs can be divided into spacecraft, aircraft, and ground-based observations. The space-based observations have been conducted by BATSE [1], the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [2], AstroRivelatore Gamma a Immagini LEggero [3], Satellite per Astronomia X, "Beppo" (BeppoSAX) [4], the RELEC experiment on the *Vernov* Satellite [5], the *Fermi* Gamma-Ray Burst Monitor (GBM) [6], and most recently the Atmosphere-Space Interactions Monitor (ASIM) [7]. To date, this fleet of spacecraft has detected thousands of TGF events.

A single detection of a TGF-like event was observed by instruments on an aircraft carrying the Airborne Detector for Energetic Lightning Emissions [8]. In addition, a few TGF events have been observed from ground level [9–12].

Soon after the discovery of TGFs, it was shown that they are associated with lightning discharges [13]. Moreover, observations made by RHESSI [2] along with detailed Monte Carlo simulations [14,15], suggested that the source of the photons was at thundercloud altitudes.

Based on space- and ground-based observations, TGFs are known to have the following general properties: time scales of submillisecond duration, photon energies up to or above 40 MeV, a fluence of about 0.1 photon cm^{-2} at satellite altitudes (450–600 km), and broad energy spectra [1,2,16].

It has been noted from observations that the broad TGF spectra can only be produced by bremsstrahlung from accelerated electrons with energy up to several tens of MeV. Therefore, it is important to understand and explain the unknown seed electron source(s) and acceleration mechanism(s) that can produce such broad spectra, which are the main objectives of this paper.

Many mechanisms have been suggested as a source of TGFs. The most important are 1) the relativistic runaway electron avalanche (RREA) mechanism [17–20], and 2) the lightning leader mechanism [21–23]. In the RREA case, relativistic seed electrons are accelerated by the large-scale ambient electric field in a thundercloud. The accelerated electrons will knock off secondary electrons by electron impact ionization, which will undergo the same acceleration process and produce avalanches of electrons. These electrons will produce photons via bremsstrahlung. Pairs of electrons and positrons will be generated due to pair production and the positrons will accelerate in the opposite direction from the accelerated electrons, producing new avalanches of electrons. In this relativistic feedback process [20], the production of TGFs should be independent of lightning activity.

A second production mechanism involves the lightning leader channel [21–23]. In this scenario, thermal electrons are accelerated to relativistic energies by very strong small scale electric fields at the tip of the lightning leader channel. The accelerated electrons again emit bremsstrahlung photons, in this case before or synchronized with the lightning return stroke, i.e., before or simultaneously with the production of strong optical emission.

Another possible scenario is a combination of the two cases. Thermal electrons are accelerated to MeV or sub-MeV energies by small-scale strong electric fields at the tip of the lightning leader. Then, these accelerated electrons continue to be accelerated in the large-scale ambient electric field, ahead of the leader channel tip. In this scenario, TGFs are expected to be produced during the development of a lightning leader channel and before the return stroke (before the production of optical emission). These suggested scenarios are still under debate, and the acceleration/emission sequence is not yet clear.

Correlations between TGFs detected by GBM and the sferics recorded by the World Wide Lightning Location Network (WWLLN) were investigated by the authors of Ref. [24], who found 15 sferics associated with a sample of 50 TGFs (association rate $= 30\%$). Of these associated events, 13 TGFs were found to have a sferic within 40 μs. The other two TGFs occurred within several milliseconds of the lightning strokes. A larger sample of 601 TGFs detected by GBM was later used to revisit the correlation between the WWLLN sferics and TGFs [25], and a similar association rate of 33% was found. Moreover, this study postulated that simultaneous very low-frequency (VLF) discharges were a result of the relativistic electron avalanche process and the nonsimultaneous VLF discharges were a result of the lightning strokes. In the most recent study of GBM TGFs [6], a large sample of 4144 TGFs was used to find a TGF-WWLLN sferic association rate of $\approx 31\%$. Additionally, this study found that the majority of these TGFs were within 200 μs of the sferic. These previous studies concluded that the electron beam in a TGF produces strong VLF emission unrelated to lightning, simultaneous to the TGF. Consequently, using just the sferic to determine the sequence of radiation in a discharge that produces a TGF may give inconclusive results. As a result, simultaneous observations of TGFs and lightning optical emissions are needed to identify the sequence of emission between TGFs and lightning.

Continuous optical emission observations can provide more valuable and accurate information about thundercloud cells that produce TGFs. This information includes the total intensity and energy of the optical emissions, lightning flash rates, and more importantly, the relative time between lightning and TGFs. Additionally, VLF and very high-frequency observations can be used to provide an estimate of the peak current (peak power) of the lightning activity.

Two previous studies of the TGF–optical emission relation were carried out in Refs. [26,27]. In the first study [26], the authors investigated the correlation between the first simultaneous detection of a TGF event detected by RHESSI and optical emissions detected by the Lightning Imaging Sensor (LIS) from the same thunderstorm. In addition, they used VLF emission from the same thunderstorm recorded by the WWLLN and the Duke University network. They postulated that the TGF was produced at the early stage of an intracloud (IC) lightning leader propagating upward. In the second study [27] the authors reported the second simultaneous detection of a TGF by RHESSI and optical emission by LIS. In light of new timing accuracy information about RHESSI and LIS, they were not able to determine the sequence of events between the TGF and the optical emission. This information about the timing accuracy led to the same conclusion about the event as in their first study [26].

Due to the scarcity of simultaneous TGF–optical emission observations, the question "Which comes first: a TGF or an optical emission?" is still an open one. In this paper, we report 22 additional simultaneous observations from space of TGFs and their corresponding optical lightning signals. In Sec. II we provide more details about the Geostationary Lightning Mapper (GLM) and GBM. In Sec. III we describe the GLM optical emission observations. In Sec. IV we present the correlation results. The discussion and conclusions are presented in Secs.

II. GLM AND GBM

The Geostationary Operational Environmental Satellite R-series 16 (GOES-R 16) was launched on November 2016 into geostationary orbit over North and South America and adjacent oceans. Instruments onboard the GOES-R 16 include the GLM, Advanced Baseline Imager (ABI), Solar Ultraviolet Imager, Extreme Ultraviolet and X-Ray Irradiance Sensor, magnetometer, and Space Environment In-Situ Suite. The GLM and ABI view the Earth continuously [28].

The GLM is a single-channel optical detector that includes a 1372×1300 pixel CCD focal plane. It measures the near-infrared emissions at 777.4 nm from total lightning activity [IC and cloud to ground] continuously day and night. The individual pixel field of view (FOV) is about 8 km. The GLM domain covers a large area enclosed within latitude in the range of $-54°$ to $54°$ and longitude in the range of 225–315°, centered at 270° during the validation period in 2017 (now GLM is centered at 255°). Much valuable information about lightning is obtained from the GLM observations, such as the time, location, intensity, and total energy of the lightning optical emission, as well as estimates of lightning flash rates and frequencies. The GLM time resolution is 2 ms and GLM reports the time of the optical emission at the midpoint of the 2 ms interval. As a consequence, GLM time is always ± 1 ms.

The *Fermi* Gamma-ray Space Telescope is a NASA space observatory that was launched in 2008 into a low Earth orbit. It includes two instruments: the Large Area Telescope, which is sensitive to gamma rays in the range 20 MeV to 300 GeV [29], and the GBM, which is sensitive to x rays and gamma rays in the range 8 keV to 40 MeV [30]. GBM consists of 12 NaI detectors (sensitive to the energy range between 8 keV to 1 MeV) and two bismuth germanate (BGO) detectors (sensitive to the energy range between 200 keV to 40 MeV). Observations made by GBM have been used to study different phenomena including TGFs and terrestrial electron beams [6,24,25,31–34].

III. OBSERVATIONS

The GLM optical emission data are used to determine the location of the thunderstorm that produced the TGF. The GLM data are categorized into three classes: events, groups, and flashes. An event is represented by one bright pixel that exceeded the background threshold. A group encompasses all adjacent events that occur in the same 2 ms frame. A flash consists of all groups within 16 km spatially and 330 ms temporally. Groups are viewed as lightning strokes. In this work, we shall use GLM events to study the relative time between a TGF and lightning. We also use events to qualitatively study the frequency of lightning activity in the thundercloud cells that produce TGFs.

The triggered GBM observations provide TGF detection times very accurately. To determine the TGF source location and time, we use lightning observations from the GLM and/or lightning location ground-based networks (if available). We search the GLM optical emission events within 800 km of the GBM's location and 20 ms from the TGF detection time to determine the TGF source location, and we account for the TGF photons' time of flight. After determining the location of the thundercloud cell that produced the TGF, we study the lightning activity at this location before, during, and after the TGF.

IV. RESULTS AND DISCUSSION

For this study, we use TGFs triggered by GBM from March 1, 2017 to December 31, 2017. In this period, 89 TGFs were triggered with 24 of them within the GLM FOV. No association with lightning seen by GLM was found for 3 of the 24 TGFs. The other 21 TGFs were all associated with optical lightning, and their source locations were within 600 km of GBM.

A. TGF source location

To determine a TGF location, we use the GLM optical data and Global Lightning Dataset (GLD360) sferic observations, and we search for lightning activity within 800 km of the GBM's location. Then, we select the closest location and time of the lightning activity with respect to the TGF detection time. This location is considered the TGF source location. It can be seen from Table I that locations (given in latitude and longitude) based on GLM data are in agreement with locations determined by GLD360. GLD360 did not detect any lightning activities that are close in location and time to 12 of the TGFs, indicating that GLM is more efficient in detecting lightning activities. GLM is designed to detect lightning optical emissions with 80% or better detection efficiency. This detection efficiency is nearly uniform over the GLM domain. This means that for a sample of 24 TGFs, GLM would be expected to detect optical lightning activity associated with 19 TGFs, consistent with the summary in Table I.

TABLE I. TGF source locations (latitude, longitude) determined using the GLM and GLD360. * indicates no signal detected.

Date	GLM	GLD360
2017-03-16	(1.23, 283.92)	(1.42, 283.88)
2017-03-25	(1.18, 295.3)	(1.160, 295.33)
2017-04-25	(6.19, 292.91)	*
2017-05-02	(11.03, 265.48)	(11.03, 265.44)
2017-05-09	(10.89, 269.38)	(11.30, 269.76)
2017-06-08	(9.39, 287.10)	*
2017-06-09	(12.73, 273.30)	(12.76, 273.20)
2017-06-19	(10.10, 276.10)	(10.06, 276.06)
2017-06-29	(17.60, 298.27)	*
2017-07-02	(8.23, 282.91)	*
2017-07-12	(21.21, 275.11)	(21.22, 275.12)
2017-08-08	(11.80, 273.29)	*
2017-08-10	(17.57, 254.75)	(17.75, 254.80)
2017-08-11	(8.98, 279.07)	*
2017-08-23	(10.44, 283.91)	*
2017-09-02	(20.84, 268.91)	*
2017-09-07	(20.19, 283.41)	*
2017-09-23	(11.31, 283.82)	(11.28, 283.87)
2017-09-28	(19.49, 266.93)	*
2017-10-08	(6.53, 282.34)	(6.52, 282.20)
2017-10-18	(7.54, 280.67)	(7.46, 280.60)
2017-03-09	*	*
2017-08-09	*	*
2017-10-17	*	(23.39, 290.13)

B. Lightning activity before, during, and after TGFs

We study the optical emission activities before, during, and after each TGF. Figure 1 shows one minute of the GLM data along with a TGF that was triggered at 23:21 UTC on March 16, 2017. The y axis shows the relative intensity of the optical emission and the x axis shows the UTC time, while the vertical blue line shows the time of the TGF. The gaps in Fig. 1 show the time intervals during which the

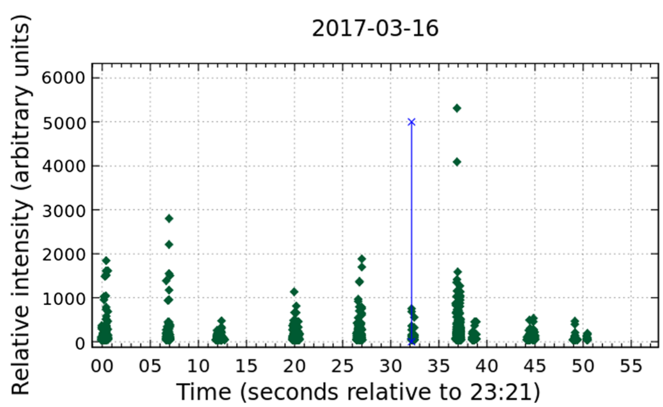

FIG. 1. Lightning activity before and after a TGF on March 16, 2017.

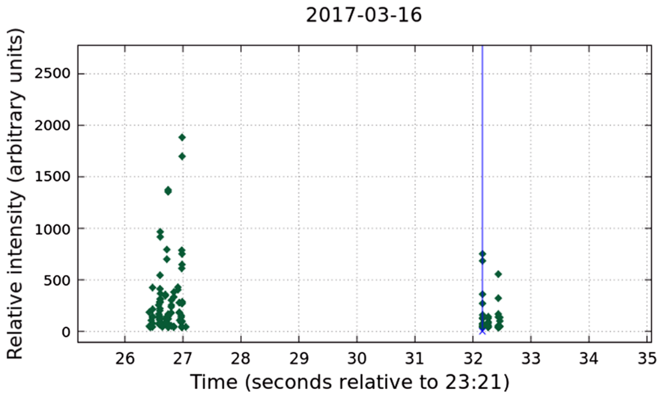

FIG. 2. Last group of lightning prior to the March 16, 2017 TGF.

cloud cell had no active lightning. In a typical thundercloud, the electric field builds up to a high value that breaks down the air and produces a lightning discharge. The electric field decreases, and the cloud takes some time to regenerate the field. It can be noted from Fig. 1 that lightning was not very frequent before the production of the TGF. The time separation between lightning flashes is on the order of a few seconds.

Figure 2 shows an expanded view of the last group of lightning activity before the same TGF. It can be seen from this figure that this thundercloud cell took around 5 s to build up an electric field before the production of the TGF. This parameter is crucial, and it may shed light on the charging rates in thunderclouds. We will address this parameter in detail using a larger sample of TGFs in a future work, where this parameter will be compared for thundercloud cells that produce TGFs with those that do not produce TGFs.

Figure 3 shows the relative time between individual TGF photons (as detected by GBM's two BGO detectors) and the lightning optical emission. The left y axis shows the measured energy of the TGF photons; these values are not corrected for saturation effects. The right y axis shows the optical emission intensity. Figures 4–7 show the same as

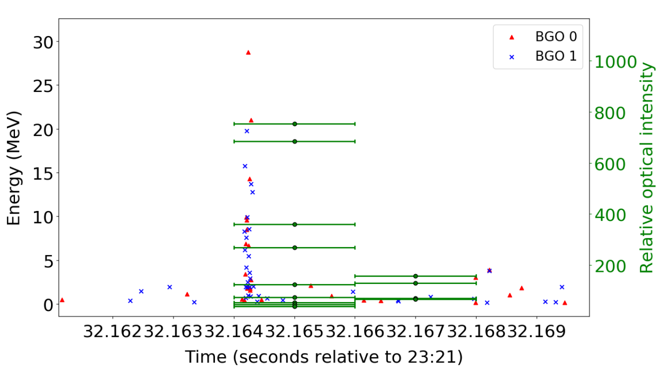

FIG. 3. Lightning activity during the March 16, 2017 TGF. The triangles and x's show the BGO energy and timing. The points with ±1 ms error bars are the GLM optical events.

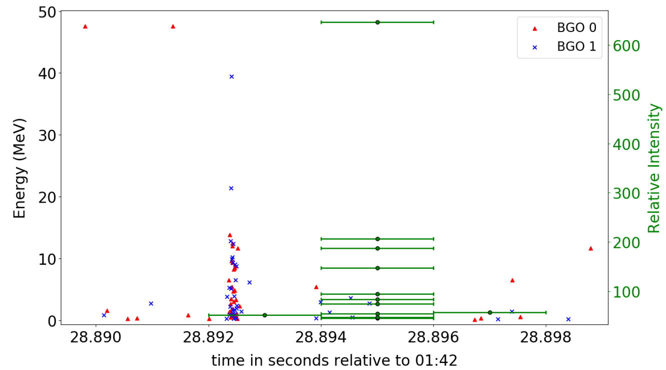

FIG. 4. Lightning activity during the 2017-04-25 TGF.

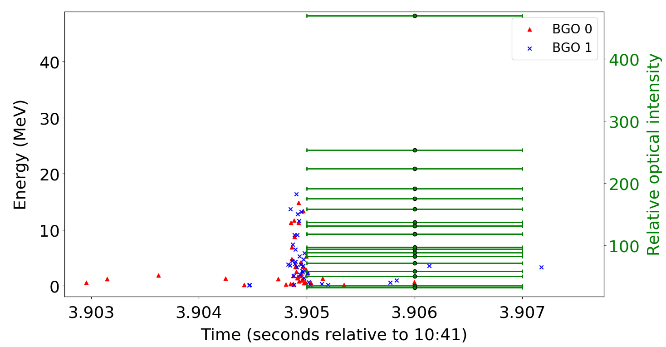

FIG. 5. Lightning activity during the 2017-05-09 TGF.

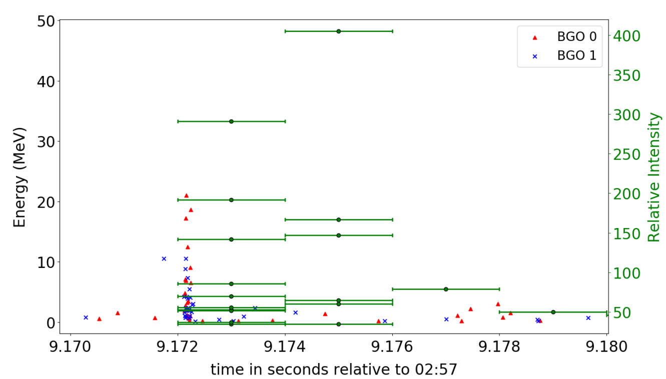

FIG. 6. Lightning activity during the 2017-06-08 TGF.

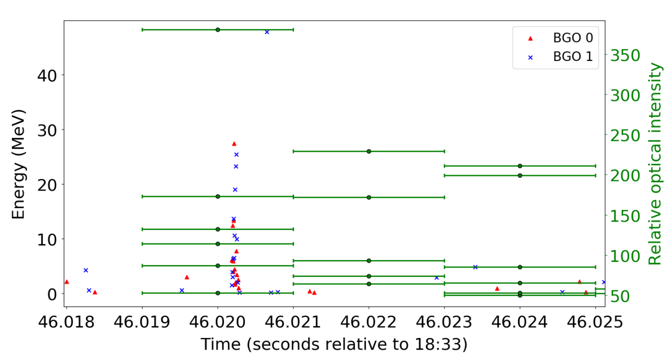

FIG. 7. Lightning activity during the 2017-09-23 TGF.

Fig. 3 for four more TGFs. In every case, the TGF is produced either just before or during the optical emission.

As mentioned previously, GLM reports the optical emission time in 2 ms intervals; as a consequence, it is not possible to determine the exact time lag between a TGF and optical emission. However, the same scenario was seen for all other TGFs, indicating that TGFs occur in sync or just prior to the optical emission (lightning stroke).

It is important to mention that for the TGF event on July 2, 2017, GLM reported an optical emission in a single pixel 2 ms before the TGF. For flashes containing one GLM event, like this case, it is hard to tell if this event is lightning or noise. Additionally, GLD360 failed to detect any lightning activity 2 ms before the TGF. We believe that this lightning activity is noise that passed through the filtration algorithm. Therefore, we have excluded this event from our analysis and discussions, leaving a sample of 20 TGFs.

The correlation results (except for the event on July 2, 2017) show that TGFs occur during or before the lightning optical emission. This suggests that a TGF may be produced during the last stage of a typical lightning leader channel development (before the production of strong optical emission). Based on the small sample we have, the correlation results suggest that TGF production is initiated by a lightning leader, perhaps augmented by RREA via the large-scale ambient electric field ahead of the leader tip.

C. Discussion

BATSE [1,35] observed 76 TGFs during its operation with a large fraction of them containing multiple pulses. The time separation between two successive pulses in most of these TGFs is 1–2 ms. The typical time scale of each step in an IC leader channel is about 1–2 ms. As a consequence, this kind of multipulse TGF might be produced by multiple steps in a leader channel, perhaps augmented by additional acceleration due to the ambient large-scale electric field. Unfortunately, GBM did not trigger any multipulsed TGFs within the GLM FOV during the period of this study. However, the previous detection of multipulse TGFs by BATSE and GBM [36] and the correlation results strongly suggest that the production of TGFs is initiated by leader processes.

A larger sample of TGFs is needed to confirm these conclusions and scenarios. For the same period, we searched the continuous GBM data for untriggered TGFs (offline TGFs) and we were able to identify 135 TGF candidates within the GLM FOV. We are planning to conduct the same study for this larger sample in future work. This large sample will help in estimating the charging rates and lightning flash rates in thundercloud cells that produce TGFs.

V. CONCLUSIONS

In light of new simultaneous observations, we studied the correlation between TGFs and lightning optical emission. We used the TGFs triggered by *Fermi*-GBM together with optical emission detected by the GLM to investigate the production mechanism of TGFs. Our study suggests that the production of TGFs is initiated by lightning leader processes and that the TGFs are produced at the last stage of typical lightning leaders.

The previous detection of multipulsed TGFs strengthens the hypothesis of the connection between leader processes and TGF production. The time separation between successive pulses in a multipulsed TGF is comparable to the time scale of leader steps.

More precise observations are needed to further investigate the TGF production mechanism. These should include TGFs, optical lightning emission, and/or sferic. Such observations can be conducted from above thunderclouds using instruments in a low Earth orbit (e.g., ASIM), balloons, or aircraft (e.g., NASA ER-2). The expected outcome from these observations is to determine the sequence of radiation between TGFs and lightning precisely and identify the physical processes that produce TGFs.

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