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Compton scattering effects on the duration of terrestrial gamma-ray flashes

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[1] Terrestrial gamma-ray flashes (TGFs) are gamma-ray bursts detected from space that are associated with lightning activity. In the present paper, we show that the shorter TGF durations (~50 μs) recently discovered by the gamma-ray burst monitor (GBM) aboard the Fermi Gamma-Ray Space Telescope are consistent with the temporal dispersion associated with the Compton scattering of photons produced by an instantaneous TGF source. This new result suggests that short TGF pulses observed from satellites correspond to very short TGF sources with durations less than ~10 μs and that the observed long TGF pulses ($\gtrsim$100 μs) may be due to overlapping of emissions produced by a sequence of elementary processes with much shorter temporal durations. **Citation:** Celestin, S., and V. P. Pasko (2012), Compton scattering effects on the duration of terrestrial gamma-ray flashes, *Geophys. Res. Lett.*, *39*, L02802, doi:10.1029/2011GL050342.

1. Introduction

[2] Terrestrial gamma-ray flashes (TGFs) are bursts of high-energy photons originating from the Earth's atmosphere in association with thunderstorm activity. TGFs were serendipitously discovered by BATSE detector aboard the Compton Gamma-Ray Observatory originally launched to perform observations of celestial gamma-ray sources [*Fishman et al.*, 1994]. These events have also been detected by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite [*Smith et al.*, 2005], the Astrorivelatore Gamma a Immagini Leggero (AGILE) satellite [*Marisaldi et al.*, 2010], and the gamma-ray burst monitor (GBM) on the Fermi Gamma-ray Space Telescope [*Briggs et al.*, 2010]. Moreover, measurements have correlated TGFs with initial development stages of normal polarity intracloud lightning that transports negative charges upward (+IC) [e.g., *Stanley et al.*, 2006; *Shao et al.*, 2010; *Lu et al.*, 2010, 2011].

[3] Although the well-established model of relativistic runaway electron avalanches (RREAs) in weak large-scale electric fields ($\ll E_k$, where E_k is the conventional breakdown threshold electric field at a given altitude) in thunderstorms had provided a very good agreement with observations [*Dwyer and Smith*, 2005], new observations have recently challenged RREA-based models [*Tavani et al.*, 2011]. Additionally, it has been shown that the number of energetic electrons produced by very high potential negative lightning leaders is consistent with the number of TGF photons received by satellites [*Celestin and Pasko*, 2011]. If TGFs are produced by mechanisms associated with the stepping of lightning leaders, the time scale of related sources may be much shorter than previously thought. In this context, we emphasize that typical measured time scales of electric field and current waveforms associated with stepping of lightning leaders are on the order of several tens of nanoseconds [e.g., *Howard et al.*, 2011, and references therein].

[4] *Østgaard et al.* [2008] have suggested that the delay of ~100 μs observed by BATSE between the arrival of high energy and low energy photons is due to Compton scattering of photons in the atmosphere. *Grefenstette et al.* [2008] have shown that the same effect took place in RHESSI measurements with a delay of ~30 μs and have established that the difference between the delays as measured by BATSE and RHESSI was due to more important detector dead time effects in BATSE [*Grefenstette et al.*, 2008]. The effect of BATSE dead time on the TGF temporal dynamics has later been confirmed by *Gjesteland et al.* [2010]. On the other hand, the typical TGF duration as observed by RHESSI is ~0.3 ms, and from BATSE measurements, *Gjesteland et al.* [2010] stated that the TGF source duration should be close to 250 μs. However, performing unprecedented time analysis with the GBM instrument aboard the Fermi Gamma-Ray Space Telescope, *Fishman et al.* [2011] have recently shown that TGF pulses could be as brief as 50 μs. In fact, this duration is even overestimated because of the dead time effects on Fermi [*Fishman et al.*, 2011].

[5] In the present paper, using Monte Carlo simulations of photons propagating through the Earth's atmosphere, we show that a TGF pulse duration of ~50 μs can be explained by the incompressible timescale of Compton dispersion as observed by satellites. This indicates that TGF sources may be much shorter that previously believed, while in agreement with satellite observations.

2. Model Formulation

[6] Although RREA-based mechanisms of TGFs production are currently challenged, the RREA process reproduces the TGF spectrum measured in a wide range of energy, over which satellite measurements are in good agreement [*Marisaldi et al.*, 2010]. Moreover, RREA produces a typical spectral signature that can be accurately approximated by an analytical formula [e.g., *Dwyer* 2008]:

$$f(\mathcal{E}_\gamma) \propto \frac{\exp(-\mathcal{E}_\gamma/\mathcal{E}_c)}{\mathcal{E}_\gamma} \tag{1}$$

where $\mathcal{E}_\gamma$ is the photon energy, $f(\mathcal{E}_\gamma)$ is the photon energy distribution function, and $\mathcal{E}_c$ is the so-called cutoff energy. In the following we fix $\mathcal{E}_c$ = 7 MeV, which is accepted to be

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close to the RREA distribution energy cutoff [*Dwyer*, 2008; *Celestin and Pasko*, 2010, Figure 4]. Additionally, assuming a given analytical formula for representing the source distribution of photons as given by equation (1) makes the present study independent of the mechanism that produces TGFs, and allows us to focus on the effects related to transport of photons through the atmosphere.

[7] The source of photons is generated to follow the energy distribution given by equation (1) with a broad beam geometry (isotropic within a 45° angle) at 15 km altitude, that is believed to be typical of TGFs [e.g., *Dwyer and Smith*, 2005; *Carlson et al.*, 2009; *Østgaard et al.*, 2008; *Dwyer*, 2008], and which is consistent with our simulation results. Note that *Gjesteland et al.* [2011] have recently found beaming angles within 30–40° to be likely. We model the photon transport in the atmosphere up to 500 km, that is the typical altitude of low-orbit satellites detecting TGFs [*Fishman et al.*, 1994; *Smith et al.*, 2005; *Marisaldi et al.*, 2010; *Briggs et al.*, 2010], using a Monte Carlo model. This model takes into account the relevant collisions between photons and air molecules for the energy range considered (10 keV to 1 GeV), similarly to previously published work [e.g., *Østgaard et al.*, 2008]. Three different collision types are taken into account: Photoelectric absorption (main process for energies up to $\sim$30 keV), Compton scattering (main process from $\sim$30 keV up to $\sim$30 MeV) and electron-positron pair production (main process >30 MeV). As for the dynamics of photons, photoelectric absorption creates a low energy cutoff on the spectrum below $\sim$50 keV [*Dwyer and Smith*, 2005; *Østgaard et al.*, 2008], Compton scattering dynamically decreases the energy of photons, and pair production process produces positrons that eventually annihilate with ambient electrons producing two new 511 keV photons in opposite directions. Important secondary effects (i.e., energetic electrons and positrons launched to the magnetosphere) are now recognized to be produced by Compton scattering and pair production of TGFs [*Dwyer et al.*, 2008; *Briggs et al.*, 2011]. However, since we focus primarily on the dynamics of photons in this study, positrons are considered to annihilate locally where pair production has occurred, and secondary Compton-produced electron bremsstrahlung is not taken into account [see *Østgaard et al.*, 2008]. The very good agreement obtained with previous publications justifies these simplifications.

[8] Because of the tremendous number of photons generated during a TGF event, at satellite altitudes the fluence approaches a value of $\sim$1 photon/cm^2 [e.g., *Carlson et al.*, 2009]. Therefore, simulating the path of every single photon through the atmosphere up to the satellite detector in order to obtain a proper statistical description of the detected photons would be extremely time consuming. On the other hand, accumulating all photons escaping to space in order to draw average information is not accurate since the physical properties of photons should depend on the distance between the subsatellite point and the TGF source location, for example due to the fact that, at larger distance from the subsatellite point, photons have experienced more Compton scattering. Indeed, *Hazelton et al.* [2009] have shown that the combined spectrum of RHESSI TGFs with thunderstorms within 300 km of the nadir point is harder than the measured TGF spectrum associated with farther sources, in agreement with Compton scattering in the atmosphere. Nevertheless, in our simulations we have observed that physical properties of photons vary with a characteristic length of a few tens of kilometer at satellite altitudes. Therefore, in our analysis, we accumulate photons in concentric rings with a horizontal width of 50 km around the TGF source location, allowing for obtaining a good statistical description of the photons while resolving the effects related to the distance from the subsatellite point. Since the area of satellite detectors is only a few square centimeters, this area is very small when compared to the area of rings discussed above. In order to simulate the time of arrival of photons as measured by detectors, we subtract the time t_s spent if the photon were to follow a straight path to the satellite detector from each time of arrival at a given arrival position. This procedure is applied to every photon arriving at any position within each of the 50 km wide collection rings. Thus, we obtain the dispersion signature of photons as captured by satellite detectors.

3. Results

[9] In the present work, we simulate 25×10^6 photons departing from the TGF source location at the same time, as if they were produced by an instantaneous TGF source. As described in the previous section, these photons are generated according to the energy distribution given by equation (1), at 15 km altitude, and isotropically within a 45° angle about the vertical axis.

[10] In order to compare simulation results and Fermi-GBM measurements, we calculate the TGF timescale using the same time measure t_{50} as in work by *Fishman et al.* [2011]. The parameter t_{50} is defined as the duration between 25% and 75% of the total number of counts detected during the event [*Fishman et al.*, 2011]. Figure 1a shows the time evolution of the cumulative sum of simulated TGF photons arrived at 500 km altitude for a distance between the subsatellite point and the TGF source between 250 km and 300 km (i.e., for one representative collection ring). Figure 1a also directly illustrates the parameter t_{50} described above.

[11] As the subsatellite-point-to-TGF-source distance increases, photons received by the satellite have experienced more Compton scattering, and therefore should demonstrate a greater time dispersion. One can clearly observe this effect in the simulation results presented in Figure 1b. In fact, one sees that for distances higher than 250 km, the Compton-scattering alone is responsible for a time dispersion greater than 50 μs.

[12] The GBM usually records TGFs with a few hundreds of photons. For the sake of comparison, Figure 2a shows the energy of photons arrived at the detector with respect to their time of arrival for a simulated 170-photon TGF, for which the subsatellite point is within 250–300 km from the source. Figure 2b shows the distribution of photons in time, or light curve, using 10 μs time bins for the same simulation. We note that although the simulated TGF source is instantaneous, the light curve shown in Figure 2b is in good agreement with the short TGF pulses discussed by *Fishman et al.* [2011].

4. Discussion

[13] When detected by the GBM, TGFs are believed to occur within $\sim$300 km of the subspacecraft point [*Fishman et al.*, 2011]. Indeed, in our simulation results the photon fluence crossing the 500 km altitude orbit surface drops by a

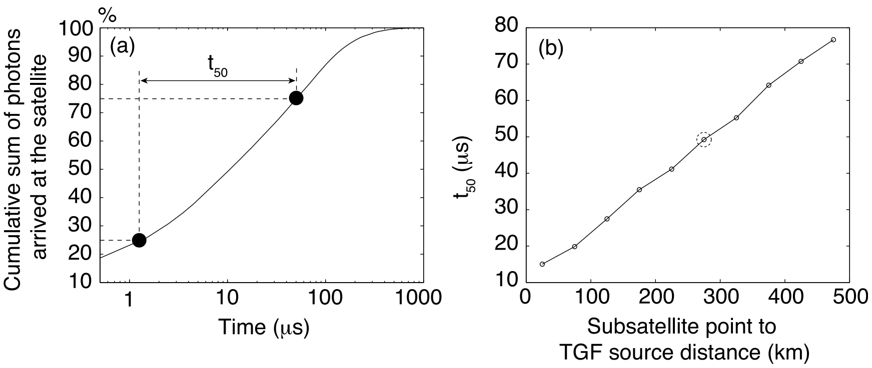

Figure 1. (a) Cumulative sum of photons arrived at the satellite versus time in the simulation and illustration of t_{50} as the duration between 25% and 75% of photons received for one event. The subsatellite point is assumed to be within 250–300 km from the TGF source (corresponding to the dashed line circle in Figure 1b). (b) The parameter t_{50} as a function of the distance between the subsatellite point and the TGF source.

factor of five at a radial distance of $\sim$300 km with respect to a case for which the satellite is directly above the TGF source, in good agreement with the observational analysis reported by *Cohen et al.* [2010] and the calculations reported by *Gjesteland et al.* [2011, Figure 3]. On the other hand, the probability that a satellite detects a TGF event from a certain distance r between the subsatellite point and the TGF source is proportional to the product of the photon fluence, the characteristic surface of the detector, and the probability of the satellite to be present at this distance. Considering the satellite location equiprobable about the axis of the TGF source, the latter is proportional to r. We find that the distance r corresponding to the maximum probability of TGF detection is approximately $\sim$200 km. A significant part of TGFs should therefore be detected from $\sim$200 km, which is also in good agreement with *Cohen et al.* [2010] and in reasonable agreement with *Collier et al.* [2011]. Consequently, Figure 1b shows that most of the TGF characteristic durations will be at least 40 μs. Moreover, because higher energy photons are less likely to Compton-scatter, the time dispersion associated with photons of lower energies is more pronounced. This characteristic is clearly shown by the overall decrease of the photons energy with the time of arrival in Figure 2a.

[14] *Fishman et al.* [2011] have found that TGFs could be as short as 50 μs with a maximum of the duration distribution function corresponding to $\sim$100 μs. Moreover, it is clearly established by *Fishman et al.* [2011] that the t_{50} durations are overestimated because of the detector dead time issues. For example, because of dead time issues, the first 10 microsecond bin in Figure 2b, that is significantly higher than the other bins, will be significantly reduced in measurements. Simply disregarding this first 10 microsecond bin brings the t_{50} duration from $\sim$40 μs to $\sim$70 μs. On the other hand, our simulation results correspond to an instantaneous source producing TGF pulse durations as detected by an ideal detector on a satellite. Despite the overestimation of t_{50} by Fermi, it is clear that the shorter TGF durations observed by Fermi-GBM are consistent with our simulation results for an instantaneous TGF source.

[15] It is worth mentioning that in the case of an instantaneous TGF source, TGF duration as measured by t_{50} is not only driven low energy photons. In fact, we observe that for a distance between the subsatellite point and the TGF source of 200 km, photons with an energy of 1 MeV would be easily detected over a 50 μs time window. Since Compton dispersion is an incompressible effect due to photon transport through the atmosphere and TGF durations as short as 50 μs were discovered by *Fishman et al.* [2011], the possibility of much shorter TGF sources is suggested by the present study. This point also supports the conclusion of *Fishman et al.* [2011] that many of the longer TGF pulses ($\gtrsim$100 μs) detected might be due to overlapping of shorter TGF pulses.

[16] *Cummer et al.* [2011] have recently shown a close association between TGFs detected by the Fermi-GBM and fast lightning processes within several tens of microseconds. In view of the results presented in the present paper, we can

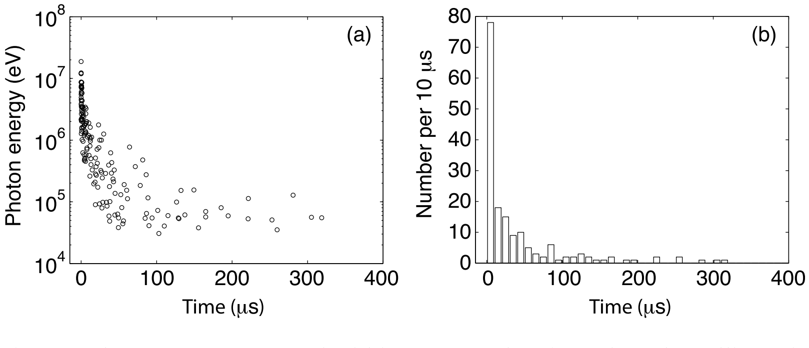

Figure 2. Simulation of a 170-photon TGF generated within 250–300 km from the subsatellite point. (a) Energy of photons arrived in the detector with respect to their time of arrival. (b) Corresponding light curve for 10 μs time bins.

surmise that a single TGF can be produced by multiple lightning processes lasting less than ∼10 μs that would be unresolved in satellite observations.

[17] In particular, electric field variation timescales during the stepping of lightning leaders can be as short as a few tens of nanoseconds [e.g., *Howard et al.*, 2011] and we have recently shown that the number and energy of runaway electrons involved in the stepping process of a high-potential intracloud negative lightning leader provide a natural explanation of TGFs [*Celestin and Pasko*, 2011]. If such processes take place on a very short time scale of a few tens of nanoseconds and are spaced by less than ∼10 μs, e.g., within a ∼100 μs fast process, only a single TGF pulse would be observed from space. In which case, the shape of the TGF pulse can reflect the longer timescale underlying electrical dynamics of the lightning leader during the stepping process or over several steps for long TGF pulses.

5. Conclusions

[18] The main contributions of this work can be summarized as follows:

[19] 1. The time dispersion of instantaneous TGF as observed by satellites has been estimated from Monte Carlo simulations of photon transport through the Earth's atmosphere.

[20] 2. A clear dependance of the characteristic time dispersion of photons in TGFs and the distance between the subsatellite point and the TGF source is demonstrated.

[21] 3. We have found that the highest probability to detect TGFs is reached at a distance of approximately ∼200 km. At this distance from the source, the theoretical TGF time dispersion is ∼40 μs, which would correspond to significantly longer TGF durations in the actual measurements because of dead time issues.

[22] 4. The results are consistent with the shorter TGFs observed by *Fishman et al.* [2011], suggesting that some TGFs correspond to sources lasting less than ∼10 μs.

[23] 5. The very fast processes involved in the stepping of lightning leaders (few tens of nanoseconds) can produce TGFs that would be observed with much longer durations (∼100 μs) from space due to overlapping of emissions produced by a sequence of elementary processes with much shorter temporal durations.

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