# Spectral dependence of terrestrial gamma-ray flashes on source distance

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[1] We use lightning sferics from the World Wide Lightning Location Network to identify storms near 362 Terrestrial Gamma-ray Flashes (TGFs). The combined spectrum of TGFs with storms within 300 km of the sub-satellite point is much harder than the spectrum of TGFs with more distant storms. When these data are compared with simulations of vertically oriented relativistic runaway breakdown, it is found that the most likely model has a source altitude of 15 km and a wide-beam geometry. We find four associations of TGFs with individual sferics geolocated to positions more than 300 km from the sub-satellite point and show that a narrow-beam source at $\geq$21 km altitude is unlikely to produce the number of high energy photons in these TGFs.

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## 1. Introduction

[2] TGFs were discovered with the BATSE instrument on the Compton Gamma Ray Observatory by *Fishman et al.* [1994] and over 800 have since been observed by the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) satellite [*Smith et al.*, 2005]. From their first detection, TGFs have been associated with thunderstorms, and some flashes from each satellite have been linked to individual lightning flashes [*Inan et al.*, 1996, 2006; *Cummer et al.*, 2005; *Stanley et al.*, 2006; *Cohen et al.*, 2006]. Estimated geolocations of lightning flashes associated with RHESSI TGFs indicate that most TGFs occur within $\sim$300 km of the sub-satellite point [*Cummer et al.*, 2005].

[3] Relativistic runaway models have been successful in modeling the combined spectrum of all RHESSI TGFs [*Dwyer and Smith*, 2005], but details of source beaming and altitude cannot be constrained by the combined spectrum because it averages over important differences among individual TGFs. One such difference is the horizontal distance from the TGF source to the sub-satellite point. As this distance increases, the spectrum of photons reaching the satellite is expected to soften (decrease in average photon energy) because bremsstrahlung radiation is intrinsically hardest at the beam center and because photons that have been Compton scattered out of the beam have a softer spectrum [*Østgaard et al.*, 2008]. The change in the TGF spectrum with distance is model dependent, so the spectral differences between TGFs that are detected close and far from the source can constrain source geometry and altitude. Unfortunately, the spectra of individual RHESSI TGFs associated with geolocated sferics cannot be directly fit with model spectra because most have <30 counts.

[4] To obtain separate spectra of TGFs with close and distant sources, we used World Wide Lightning Location Network (WWLLN) data to identify storm locations at the times when TGFs were detected. TGFs were then sorted by the distance from the sub-satellite point to the nearest potential source storm. WWLLN is a global VLF network that records times and locations of lightning flashes with a mean accuracy of 15 km [*Rodger et al.*, 2008]. *Jacobson et al.* [2006] showed that despite its low detection efficiency for a single flash, WWLLN provides a spatially accurate and complete census of storms.

## 2. Data and Analysis

[5] We consider 362 TGFs detected by RHESSI between October 1, 2003 and December 31, 2005 (823 days) for which concurrent WWLLN data are available. This time range starts after the time-of-group-arrival (TOGA) algorithm was implemented in WWLLN [*Rodger et al.*, 2005] and ends before radiation damage to the RHESSI detectors affected the spectral quality too much [*Grefenstette et al.*, 2008b]. For each TGF, all WWLLN lightning flashes within ±20 minutes were accumulated to locate lightning-producing storms. The TGFs were divided into two categories: those with lightning flashes within 300 km of the sub-satellite point (316 TGFs), and those without (46 TGFs). To evaluate the spectral differences between the categories, the combined spectrum for each category was divided by the combined spectrum of all 362 TGFs. The spectrum of TGFs with only distant lightning flashes is much softer than the spectrum of TGFs with closer ones, see Figure 1. This implies that lightning flash locations are good proxies for TGF sources because the spectrum of TGFs is expected to soften with distance.

## 3. Runaway Breakdown Models

[6] A Monte Carlo simulation of runaway breakdown in air similar to the one used by *Dwyer and Smith* [2005] was

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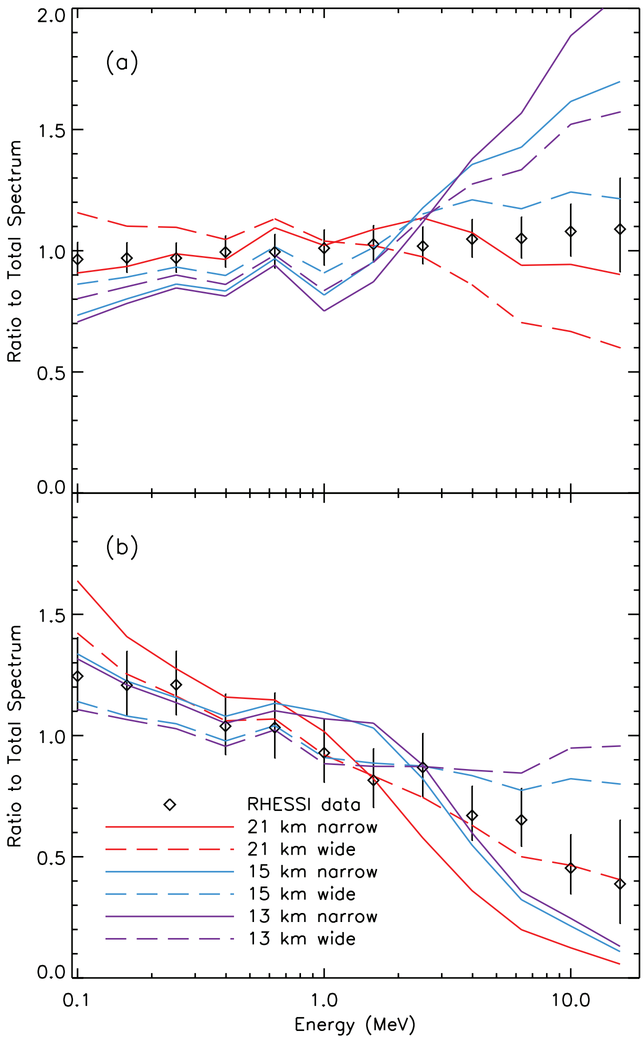


**Figure 1.** Ratios of the spectra of close and distant TGFs to the combined spectra of all 362 TGFs, with runaway breakdown models. (a) TGFs with close lightning flashes and models with close sources. (b) TGFs with only distant lightning flashes and models with distant sources.

used to model the spectra of TGFs originating more or less than 300 km from the sub-satellite point. The simulation includes all the important interactions of energetic electrons, positrons and photons in air. For a detailed description of the included physics, see *Dwyer* [2007].

[7] In the first phase of the simulation, the runaway avalanche was allowed to develop in a region with a uniform downward electric field. Outside this region the field was set to zero. The runaway electrons were propagated until they left the avalanche region and stopped. The solid-angle distribution of the photons produced in this phase of the simulation (Figure 2a) shows that the photons are beamed upward, with the highest energy photons in a narrower cone. The photons were then propagated through the atmosphere using GEANT3 (with the 2003 release of the CERN libraries), a standard high-energy particle transport code used in particle physics and astrophysics [*CERN Application Software Group*, 1993].

[8] We also considered a wider beam that might result from divergence in the electric field in the avalanche region. The wider distribution is generated by convolving the original distribution with a Gaussian in solid angle, widening the beam while preserving its energy structure (Figure 2b).

[9] To compare the models with data, it is important to consider the intensity threshold for detecting a TGF. As the photons propagate through the atmosphere they are sometimes Compton scattered to very large angles. These photons have a much softer spectrum than those in the main the beam, so they can have a significant effect on the model spectrum. Because they are scattered into a large solid angle, the satellite is more likely to fly into the path of the Compton-scattered photons than the main beam. The flux of Comptonized photons is much lower than the flux in the beam, however, so the RHESSI search algorithm is less likely to identify the TGF. The model spectra of *Dwyer and Smith* [2005] only included emission into angles at which the flash would appear at least half as bright to the satellite as a flash directly below it. This threshold was based on the range of observed fluences in RHESSI TGFs and the assumption that all TGFs have the same intrinsic brightness, so the observed fluence depended only on source distance.

[10] A more sophisticated threshold was developed for this paper using the knowledge of source distance provided by WWLLN. First, the counts detected by RHESSI from all 362 TGFs were sorted into a histogram based on the distance from the nearest lightning flash to the sub-satellite point. Next, the model photons were binned by horizontal distance from the source and the spectrum from each distance bin was convolved with the instrument response to generate the count spectrum that would be detected by RHESSI. Finally, the number of model counts in each distance bin was re-normalized to the number of counts actually detected by RHESSI in that distance bin. One major advantage of this method is that any deadtime effect on the number of detected counts versus distance is duplicated in the models (see section 5). This method systematically places the source too near the satellite, because the distance is based on the nearest lightning flash. The result is that the model spectra are harder than they would be if the actual source distances were known.

[11] Three source altitudes (13 km, 15 km, and 21 km) and two types of beaming (narrow and wide) were considered. The models that best fit the combined spectra of all 362 TGFs are the 21 km narrow model and 15 km wide model, as by *Dwyer and Smith* [2005] (the wide-beam used in that paper was isotropic in a 45° half-angle cone). To compare the models with the TGFs separated by source distance, the distance-binned model spectra were combined inside and outside of 300 km and then normalized to make two spectra for each model: for TGFs greater and less than 300 km from the source (Figure 1). The TGFs with close and distant sources are best fit by the 21 km narrow and 21 km wide models respectively; the 15 km wide model is the second-best fit for both. No single model fits all the data perfectly, but the 15 km wide model has the lowest total $\chi^2$ across both categories.

[12] To quantify the effect of the distance bias, the same re-normalization procedure was carried out, but with the

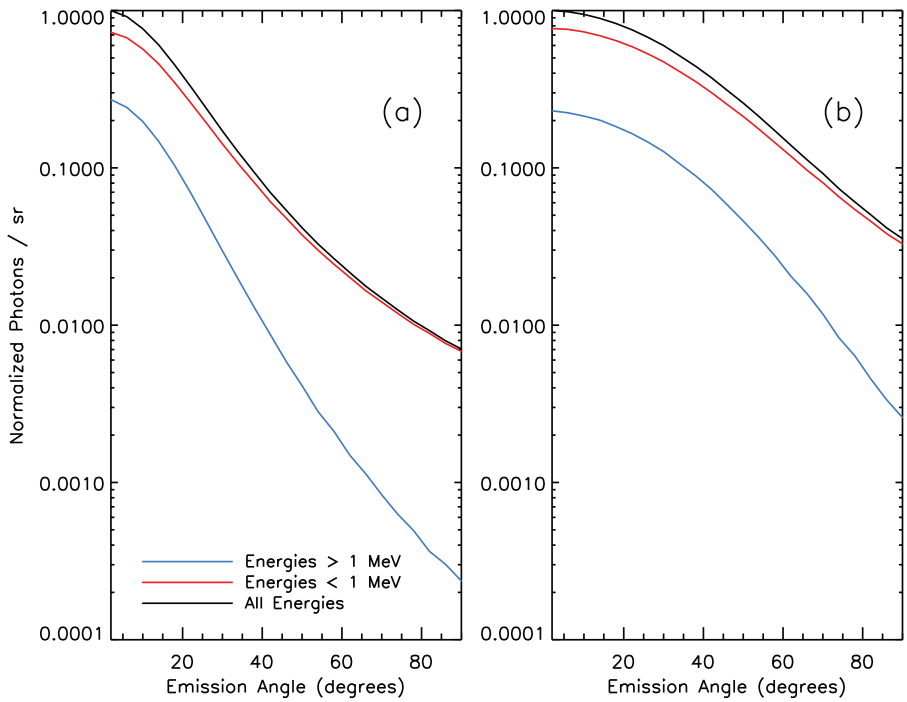


**Figure 2.** (a) Intrinsic beam shape from relativistic runaway simulations. Note the energy structure of the beam, with the high energy photons concentrated in a narrower emission cone than the low energy photons. (b) Wide beam shape from the convolution of the intrinsic beam shape with a gaussian in solid angle.

source distance defined for each TGF using a randomly selected lightning flash within 20 minutes and 600 km of the TGF, rather than the nearest one. This randomization was repeated many times, providing an upper limit on how much the models might change if the actual source locations were known, since randomly selecting a lightning flash as the source will generally overestimate the distance. This algorithm produced models that were all softer than when the nearest lightning flashes were used (see Figure 3), with the largest changes occurring in the narrow models inside 300 km and very little change in the 15 km wide-beam model. Using the randomly selected lightning flashes, the 15 km wide-beam model was the best fit for the TGFs with close and distant sources, and it was the second best fit for the combined spectrum of all the TGFs, after the 13 km wide model. We conclude that the bias introduced by using the nearest lightning flash affects the narrow models the most and that removing the bias would make the 15 km wide-beam model an even better fit to all the data.

## 4. TGFs With Distant Sferic Geolocations

[13] We found four sferics associated with TGFs and geolocated to positions more than 300 km from the sub-satellite point (Table 1). Three of these sferics were geolocated by the Los Alamos Sferic Array (LASA) following the analysis procedures outlined by *Stanley et al.* [2006] and the fourth was geolocated both by the Zeus network [*Chronis and Anagnostou*, 2003] and by magnetic field sensors at Duke University [after *Cummer et al.*, 2005]. The highest-energy gamma-rays in these distant geolocated TGFs constrain the viability of narrow-beam models.

[14] A bootstrap Monte Carlo method was used to compare the number of high energy counts observed in each TGF with the number that would be expected from a narrow-beam source at 21 km. First, model spectra were generated in 100 km wide distance bins and convolved with the instrument response. Then, for each geolocated TGF, the model spectrum for the appropriate distance bin was combined with the background spectrum for that TGF taken from the First RHESSI TGF Catalog [*Grefenstette et al.*, 2008b] to generate an expected spectrum. An energy threshold that contained the most energetic 5% of model counts was selected and the number of counts in the real TGF with energies above this threshold was compared with the number in ten million simulated TGFs. The fraction of model TGFs with at least as many high energy counts as were observed is shown in the last column of Table 1 (Observation Probability) for a 21 km narrow-beam model. The product of these four probabilities is $4.8 \times 10^{-5}$. The product of four random, uniformly distributed probabilities is lower than this 1.1% of the time. This is the likelihood that our set of four localized TGFs is consistent with the 21 km narrow-beam model. For comparison, all the other models considered in Section 3 have a corresponding likelihood of $\geq$41%.

[15] The last three TGFs in Table 1 happened after the time period considered in Sections 2 and 3, when some radiation damage had occurred, decreasing the average energy of the counts. The instrument response used in this analysis is therefore not the true RHESSI response for these TGFs. The simulation thus overestimates the probability of detecting high energy counts, so the true probabilities are even lower than reported in Table 1.

## 5. Discussion

[16] Estimating TGF source locations using sferic data has proved a powerful tool to examine models of TGF

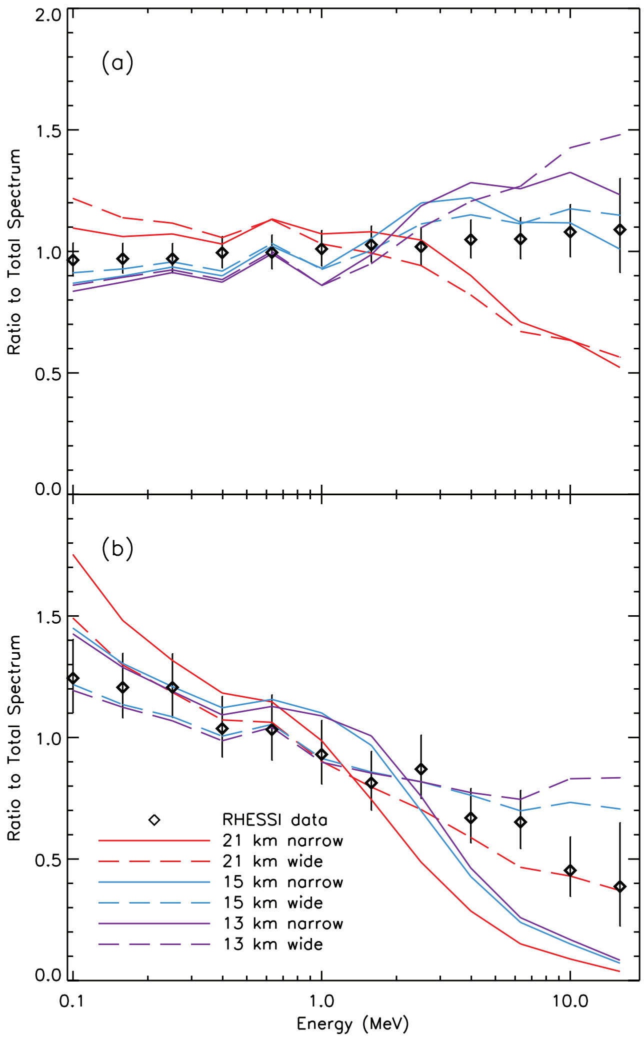


**Figure 3.** Data as in Figure 1, models using the random lightning flash algorithm instead of the nearest lightning flash algorithm (see text for details).

production. The distance from the estimated source location to the sub-satellite point sorts TGFs into categories with very different spectra, something no other parameter has been observed to do [*Grefenstette et al.*, 2008b], and increases the constraints on the models. The results of the modeling are consistent with *Dwyer and Smith* [2005] and suggest that the 15 km wide beam is the most likely source geometry, but none of the models considered perfectly fit the spectra of both TGFs with close sources and TGFs with distant sources. The time delays between the hard and soft components of the TGFs with close sources are consistent with those reported for all RHESSI TGFs by *Grefenstette et al.* [2008a], who used a similar 15 km wide-beam model. The lower statistics for the TGFs with distant sources prevent a good measurement of the time delay in that category.

[17] The viability of models with vertical narrow beams can be constrained by the number of high energy photons in individual TGFs with associated geolocated sferics at >300 km. We find that a 21 km source with the beam profile shown in Figure 2a is unlikely to produce as many high-energy counts as we observe in the four TGFs examined here. Models with even narrower beams and higher altitudes would be in even greater disagreement with these data. *Østgaard et al.* [2008] found that a significant portion of BATSE TGFs were likely produced above 30 km, but it has since been reported that the BATSE TGFs are suffering from significant deadtime [*Grefenstette et al.*, 2008a], which can affect the observed spectra and therefore the apparent production altitude. Either the inclusion of this effect, or modeling of tilted high-altitude beams, may resolve the question of whether there is a high-altitude subset of TGFs.

[18] It was recently discovered [*Grefenstette et al.*, 2008b] that the brightest RHESSI TGFs are likely to be suffering from saturation of the detectors. There are two saturation effects that will change the detected spectrum of TGFs with close sources: deadtime and pileup. Deadtime occurs when a photon enters a RHESSI detector less than 9 $\mu$s after the previous one and is vetoed [*Smith et al.*, 2002]. Deadtime does not directly change the observed spectrum, but because the brightest part of the TGF is also the hardest [see *Grefenstette et al.*, 2008a], the detected spectrum for TGFs affected by deadtime will be softer than the true spectrum. Pileup occurs when two photons enter a RHESSI detector less than 1 $\mu$s apart and their energy is summed into one count, making the observed spectrum harder. To quantify the spectral effects of deadtime and pileup, we ran Monte Carlo simulations with typical TGF time profiles and 0% or 50% peak deadtime. We find that above 5 MeV, deadtime results in a 5% decrease in the number of observed counts, while pileup causes a 20% increase, for a net increase in high energy counts of about 15%. By contrast, the difference between the two best models in Figure 1a is more than 30%. The analysis in section 4 and the data in Figure 1b are unlikely to be affected by deadtime or pileup because TGFs with distant sources are expected to be the least saturated.

**Table 1.** TGFs With Sferic Geolocations More Than 300 km From the Sub-satellite Point[a]

| Date | Detection Network | Source Distance (km) | Energy Threshold (MeV) | Total Counts | High-Energy Counts | Observation Probability |
|---|---|---|---|---|---|---|
| Aug 4, 2004 | Duke & Zeus | 535 | 1.7 | 18 | 2 | 0.22 |
| Sept 11, 2006 | LASA | 371 | 3.5 | 22 | 5 | 0.0034 |
| June 11, 2007 | LASA | 319 | 3.5 | 22 | 2 | 0.28 |
| June 16, 2007 | LASA | 374 | 3.5 | 19 | 2 | 0.23 |

[a]See text for details.

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