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The rarity of terrestrial gamma-ray flashes

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[1] We report on the first search for Terrestrial Gamma-ray Flashes (TGFs) from altitudes where they are thought to be produced. The Airborne Detector for Energetic Lightning Emissions (ADELE), an array of gamma-ray detectors, was flown near the tops of Florida thunderstorms in August/September 2009. The plane passed within 10 km horizontal distance of 1213 lightning discharges and only once detected a TGF. If these discharges had produced TGFs of the same intensity as those seen from space, every one should have been seen by ADELE. Separate and significant nondetections are established for intracloud lightning, negative cloud-to-ground lightning, and narrow bipolar events. We conclude that TGFs are not a primary triggering mechanism for lightning. We estimate the TGF-to-flash ratio to be on the order of 10^{-2} to 10^{-3} and show that TGF intensities cannot follow the well-known power-law distribution seen in earthquakes and solar flares, due to our limits on the presence of faint events. **Citation:** Smith, D. M., et al. (2011), The rarity of terrestrial gamma-ray flashes, *Geophys. Res. Lett.*, *38*, L08807, doi:10.1029/2011GL046875.

1. Introduction

[2] Terrestrial Gamma-ray Flashes (TGFs) have been known since their discovery in 1994 to be associated with thunderstorms [*Fishman et al.*, 1994] and individual lightning flashes, detected by their radio emission (sferics) [*Inan et al.*, 1996]. It has been suggested [*Gurevich et al.*, 1999; *Dwyer*, 2005] that the same processes of relativistic runaway that causes gamma-ray production by electron bremsstrahlung may also initiate lightning within thunderclouds.

[3] The observed TGF rate from space is much lower than that of lightning *Smith et al.* [2005]. Spectral evidence suggests that the gamma-rays usually originate at altitudes comparable to the highest thunderstorm cells (15–21 km) [*Dwyer and Smith*, 2005; *Carlson et al.*, 2007; *Østgaard et al.*, 2008; *Hazelton et al.*, 2009]. Since gamma-rays are absorbed by the atmosphere, *Williams et al.* [2006] suggested that the scarcity of TGFs as seen by satellites might be an artifact of their usual production site being too low in the troposphere. The equatorial concentration of TGFs relative to lightning would then be due to the higher tropopause and correspondingly higher storm tops in the tropics. More recently, discoveries of differences between the geographical distributions of TGFs and lightning not related to tropopause height [*Smith et al.*, 2010] but correlated to elevated mixed phase (high liquid water and ice content) [*Splitt et al.*, 2010] have suggested that the differing ease of gamma-ray escape with tropopause height does not explain all the differences between lightning and TGF occurrence. In other words, TGFs may not be associated with all lightning, but may require particular additional conditions.

[4] We present upper limits on gamma-ray emission from the Airborne Detector for Energetic Lightning Emissions (ADELE), passing near lighting in Florida storms at ~14 km altitude. Until these flights, it was possible to hypothesize that every lightning flash had a TGF associated with it, either as part of the initiation mechanism, as part of the leader process, or as an after-effect of the movement of charge. We demonstrate that this is not the case.

[5] The only previous high-energy measurements from an airplane were by George Parks, Michael McCarthy and collaborators [*Parks et al.*, 1981; *McCarthy and Parks*, 1985], who found surges in x-ray count rate on the order of a second that were terminated by lightning flashes. At that time, the millisecond TGFs had not been discovered, and none were reported from those flights. Similar results (surges but no TGFs) were reported from balloon-borne instruments by Kenneth Eack and collaborators [*Eack et al.*, 1996a, 1996b].

2. Instrument and Data

[6] ADELE uses three kinds of scintillators (5″ × 5″ NaI, 5″ × 5″ plastic, and 1″ × 1″ plastic), optimized to handle successively higher gamma-ray fluxes. There is one of each type in two sensor heads, one facing upwards and the other downwards. Here we use data from the large plastic scintillators summed over energies >300 keV, for which the number of counts per 50μs interval was collected continuously. These detectors can count up to 3×10^6 c/s without significant deadtime and each has an effective area of 65 cm^2 when responding to a spectrum typical of TGFs.

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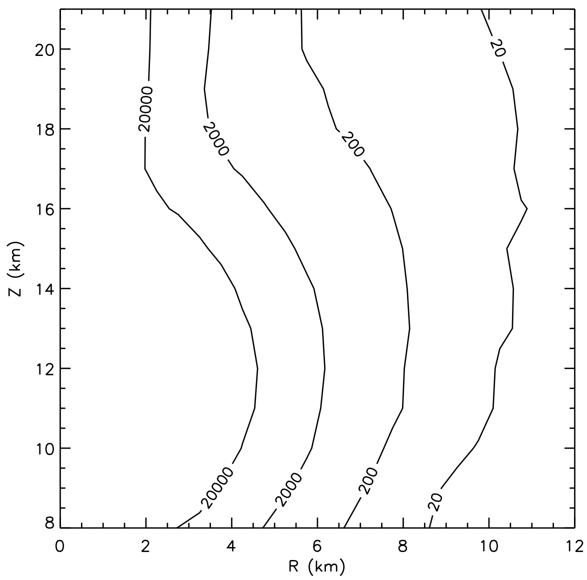

Figure 1. Expected ADELE counts (>300 keV) from a TGF originating at the altitude on the vertical axis, at a radial distance given by the horizontal axis. The 20-count contour represents the detection limit. The aircraft is assumed to be within an altitude range of 14.0–14.5 km.

[7] ADELE was flown above and around thunderstorms in the continental United States, mostly Florida, in August 2009, on the Gulfstream V (GV) jet operated by the National Center for Atmospheric Research (NCAR) on behalf of the National Science Foundation (NSF). The first ADELE flight took off from Rocky Mountain Municipal Airport on 7 August 2009 and continued on toward thunderstorm activity in Montana. After a ferry flight of the GV to Melbourne, Florida, eight more ADELE flights took place within or near Florida, from 16 August through 2 September. ADELE was in the air for a total of ~37 hours.

3. Results

[8] Figure 1 shows contours of the counts >300 keV expected from a TGF originating at different altitudes and radial distances from the plane. The plane is assumed to be at 14 km, typical for the GV flights, and a TGF is assumed to produce 10^{17} gamma-ray photons, an intensity that gives the typical TGF photon flux seen from space if originated at 15 km. The 20-count contour is the smallest signal we can reliably identify as statistically significant relative to the background.

[9] We used a three-stage Monte Carlo simulation to derive these contours. In the first stage, the x-ray and gamma-ray emission from a relativistic runaway avalanche was calculated using the full Monte Carlo simulation of *Dwyer* [2007], with a vertical, downward-pointing, sea-level-equivalent field of 400 kV/m [*Dwyer and Smith*, 2005] such as might appear between the upper positive and main negative charge centers of a thundercloud. The simulated avalanche region extends over 87 g cm^{-2} of atmosphere. Energetic seed electrons are injected into the start of the avalanche region with an exponential energy spectrum that is known to be a self-similar solution to the avalanche process, and increase in number exponentially until the high-field region ends. Most bremsstrahlung gammas are therefore created in a narrow altitude range just before and after the field ends; for example, 90% are produced between 11.4 km and 12.2 km if the end of the high-field region is placed at 12 km. The bremsstrahlung beam has a width (half width at half maximum) of 18° [see *Hazelton et al.*, 2009, Figure 2a]; any further broadening only increases TGF detectability at large horizontal distances by directing more photons toward the aircraft. Photons detected outside of this beam are mostly either Compton scattered or produced by positrons. These positrons, which are created by pair production from bremsstrahlung gamma-rays, also run away and produce a downward bremsstrahlung beam.

[10] The positrons can also seed additional runaway electrons avalanches, resulting in a positive feedback effect, which may be involved in producing TGFs [*Dwyer*, 2003, 2007, 2008]. The simulation we used was run in the regime of very weak feedback, but the spectrum and angular distribution of the photons generated does not depend strongly on either the amount of feedback or the field strength within the range 300–3000 kV/m [*Dwyer*, 2008].

[11] In the second stage of the simulation, the bremsstrahlung photons created in the first stage are propagated through the atmosphere between the emission region in the thundercloud and the ADELE aircraft. The atmospheric simulation is run with the GEANT3 package [*GEANT Team*, 1993]. The atmosphere is modeled as 160 layers, each 500 m thick, with density versus altitude given by the method described by *Smith et al.* [2010]. The photon flux at aircraft altitude is recorded as a function of distance, angle and energy, and propagated through a mass model of the aircraft and detectors, also using GEANT3, to generate the expected counts seen by the detectors (Figure 1).

[12] Every lightning discharge occurring within the 20-count contour of Figure 1 with no simultaneous gamma-ray emission demonstrates that TGFs are not an intrinsic part of lightning. We use the term "discharge" for any impulsive event that can produce a separate, distinguishable sferic, including both CG strokes and discrete IC events within a complex IC flash. We acquired three sets of commercial sferic data to identify lightning discharges near ADELE. United States Precision Lightning Network (USPLN) stroke data were provided by the Research Aviation Facility of the NCAR Earth Observing Laboratory (EOL), the group that flies the GV. Stanley Heckman of AWS Convergence Technologies, Inc. graciously provided sferic data from the Weatherbug Total Lightning Network (WTLN). One of us (RJB) provided National Lightning Detection Network (NLDN) data. All data sets include discharge polarity and classification (CG or IC).

[13] Summing over all the ADELE flights and all three sferic networks, there were 1213 unique discharges within 10 km, with redundancies (the same discharge identified by multiple networks) removed (Figure 2, bottom right). All but one of these discharges had no gamma-ray signal above our 20-count sensitivity limit, indicating that no TGF occurred. The one TGF observed, from a +IC event very close to 10 km from the plane, is the subject of a paper in preparation. There were 133 unique discharges within 4 km. For these events, at least 2000 counts would have been detected for any TGF with the top of its avalanche region below 16 km and above 8 km. This is a very strong limit,

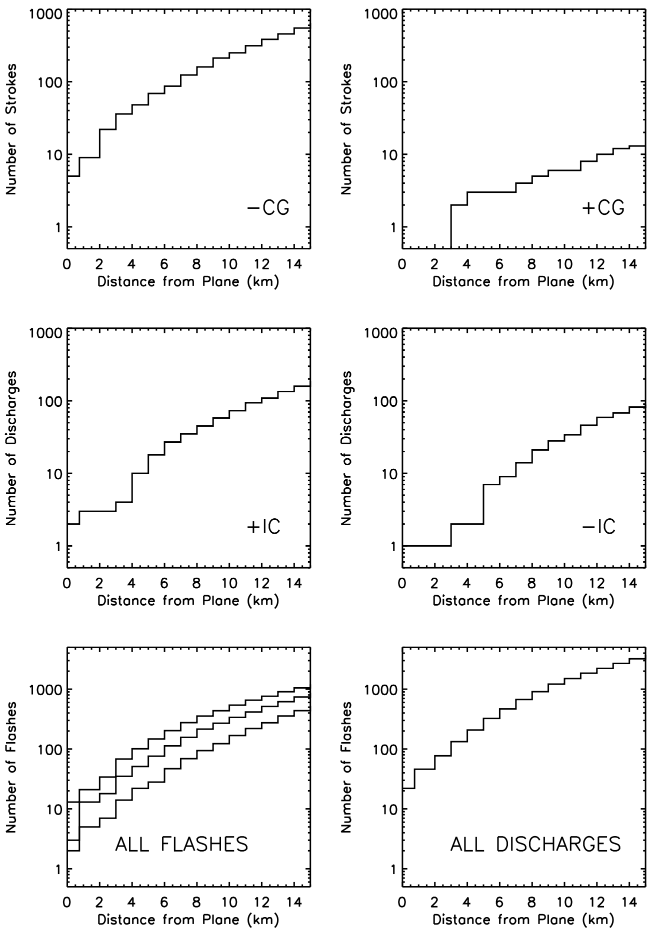

Figure 2. Discharges within distance *R* of ADELE, as a function of *R*. (top and middle) Discharges with a confirmed type (see text). (bottom left) Flashes (with distances calculated three ways – see text) and (bottom right) individual discharges from all networks, whether confirmed or not, with duplication between networks removed.

implying that no event making more than 1% of the gamma-rays associated with TGFs seen from space could have occurred. Even TGFs above 16 km, which we consider unlikely for non-tropical convection, would produce >200 counts at <4 km, and are ruled out at an order of magnitude below observed TGF intensities.

[14] We combined all discharges <32 km from the plane with no gap >1 s between them into a single flash. Since multiple discharges associated with the same flash can have different positions, we use three position estimators: the closest discharge to the plane, the average position, and the farthest discharge. These give different number-vs-distance histograms (Figure 2, bottom left). For the three estimators, the numbers within 10 km are 436, 270, and 123, respectively, and within 4 km the numbers are 68, 35, and 14.

[15] Figures 2 (top) and 2 (middle) show similar histograms for individual discharges sorted by type: positive and negative cloud-to-ground (+CG and −CG) and intracloud (+IC and −IC, with the polarities defined as moving positive charge in the same direction as CG flashes of the same sign). For these subsets of the data, we required two networks to have identified the same discharge within a tighter match criterion of ≤1 ms separation in time and <5 km separation in distance. When there was a disagreement in classification (CG or IC) between NLDN and USPLN, or in polarity between any pair of networks, we eliminated the discharge from these histograms (WTLN CG/IC classifications were still considered preliminary as of summer 2009). Discharges with peak current less than 10 kA identified by any network as CG were reclassified as IC [*Cummins et al.*, 1998]. Within 10 km of the plane, we found 212 −CG strokes, 6 +CG strokes, 58 +IC discharges, and 28 −IC discharges. None of these events could therefore have been associated with TGFs of typical intensity (as seen by spacecraft). Within 4 km of the plane, we found 36 −CG, 2 +CG, 4 +IC, and 2 −IC discharges. For these events, even a TGF of only 1% of typical intensity could have been seen, and can therefore be ruled out.

[16] ADELE's range for detection (Figure 1) is almost uniform for TGF production altitudes of 9–14 km. Our upper limits on IC flashes within this range are therefore not sensitive to their exact altitude distribution. Sferics associated with TGFs seen from space over Florida cover just this range [*Stanley et al.*, 2006; *Shao et al.*, 2010]. *Koshak and Krider* [1989] show that the lower negative in Florida storms is typically around 8~km, so most IC flashes should be above that altitude and therefore in our sensitive range. Our limits for CG events are really for any processes at IC altitudes associated with the flash that produces the CG strokes. Future flights including comparisons with lightning mapping array data would allow us to identify such processes.

[17] The uncertainties in positions from the sferic networks are ~1 km and most matches for the same discharge were closer than 2 km. Thus only a minority of discharges should have been incorrectly included inside the <10 km and <4 km boundaries.

[18] Two specific types of lightning discharge have been associated with TGFs: Narrow Bipolar Events (NBEs) [*Smith et al.*, 1999; *Stanley et al.*, 2006; *Shao et al.*, 2010] and +IC discharges related to a charge moment change over +40 C km early in IC flashes [*Cummer et al.*, 2005; *Lu et al.*, 2010]. We analyzed data from the Duke University magnetic sensors at Durham, North Carolina and Vero Beach, Florida to identify these types of discharges. The low frequency (LF) data (bandwidth 30–400 kHz and sampling frequency 1 MHz) continuously recorded at Vero Beach during ADELE's flights were examined to identify NBEs, defined as having a full width at half maximum of the initial field change pulse of 5–8μs. For +IC events not associated with an NBE, the charge moment change was calculated from the 0.1–500 Hz ultra-low-frequency signals recorded near Duke.

[19] There were five NBEs within 15 km of ADELE during the Florida flights, and two were within 10 km of ADELE (7.3 km and 8.2 km) Since these two NBE events did not show the expected number of gamma-rays for a TGF at their distances (see Figure 1), we conclude that not all NBE discharges are associated with TGFs, although some have been [*Stanley et al.*, 2006; *Shao et al.*, 2010].

[20] There were also four high-charge-moment change (>+40 C km) +IC strokes within 15 km of ADELE. The closest was at 11.7 km range, and thus any associated TGF would be just on the edge of detectability. More observations are needed to determine if +IC classification and high

charge moment change are always sufficient conditions to produce a TGF.

4. Conclusion

[21] The first flights of ADELE reveal that TGFs of the intensity seen from space are not associated with most lightning discharges in Florida thunderstorms. This statement can be made for lightning generically, for IC discharges specifically, for any IC-altitude processes near the return-stroke positions of −CG and +CG lightning, and for two NBE events less than 10 km from the plane. These observations rule out, for the first time, TGFs as the primary triggering mechanism for most lightning. We do not rule out a role for some other relativistic process that has a much lower gamma-ray yield than a TGF.

[22] We also rule out a large population of TGFs much weaker than those seen from space. From Figure 1, we should be able to see, within 4 km, TGFs 1000 times fainter than the event we modeled. If the integral distribution of TGF intensities followed a power law like earthquakes [*Gutenberg and Richter*, 1944] or solar flares [*Dennis*, 1985], of index ≈−0.8, then we should observe 250 times as many events when sensitivity improves by a factor of 1000. Having passed by 133 discharges within 4 km and 1213 within 10 km, one normal TGF in the latter population would predict 27 faint TGFs in the former if the power-law distribution applied. Thus we conclude that the distribution of TGFs at intensities below those seen from space is much flatter than this power law; whether there is actually a threshold intensity remains to be seen.

[23] Confirming the rarity of TGFs in other storm environments (such as tropical storms, where they are seen more commonly from space) is important for our confidence in aviation safety. It has been shown that aircraft passengers and crew could receive a radiation dose up to 0.1 Sv from flying directly through the top of the avalanche region [*Dwyer et al.*, 2010]. Based only on our Florida data, with one TGF seen among 123–436 nearby flashes, the global TGF frequency is on the order of 10 per minute, given a lightning rate of 44 ± 5 per second [*Christian et al.*, 2003]. Both the single positive detection and the use of only one geographical region render this number uncertain, perhaps by an order of magnitude.

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