JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, D09206, doi:10.1029/2009JD012039, 2010

Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft

J. R. Dwyer,[1] D. M. Smith,[2] M. A. Uman,[3] Z. Saleh,[1] B. Grefenstette,[2] B. Hazelton,[2] and H. K. Rassoul[1]

Received 9 March 2009; revised 17 August 2009; accepted 16 November 2009; published 15 May 2010.

[1] Using recent X-ray and gamma-ray observations of terrestrial gamma-ray flashes (TGFs) from spacecraft and of natural and rocket-triggered lightning from the ground, along with detailed models of energetic particle transport, we calculate the fluence (integrated flux) of high-energy (million electronvolt) electrons, X rays, and gamma rays likely to be produced inside or near thunderclouds in high electric field regions. We find that the X-ray/gamma-ray fluence predicted for lightning leaders propagating inside thunderclouds agrees well with the fluence calculated for TGFs, suggesting a possible link between these two phenomena. Furthermore, based on reasonable meteorological assumptions about the magnitude and extent of the electric fields, we estimate that the fluence of high-energy runaway electrons can reach biologically significant levels at aircraft altitudes. If an aircraft happened to be in or near the high-field region when either a lightning discharge or a TGF event is occurring, then the radiation dose received by passengers and crew members inside that aircraft could potentially approach 0.1 Sv (10 rem) in less than 1 ms. Considering that commercial aircraft are struck by lightning, on average, one to two times per year, the risk of such large radiation doses should be investigated further.

Citation: Dwyer, J. R., D. M. Smith, M. A. Uman, Z. Saleh, B. Grefenstette, B. Hazelton, and H. K. Rassoul (2010), Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft, *J. Geophys. Res.*, *115*, D09206, doi:10.1029/2009JD012039.

1. Introduction

[2] Our atmosphere emits high-energy radiation under a wide range of circumstances. X-rays and gamma rays have been found to be emitted by thunderclouds using both in situ and ground-based observations [*Shaw*, 1967; *Parks et al.*, 1981; *McCarthy and Parks*, 1985; *Eack et al.*, 1996; *Brunetti et al.*, 2000; *Chubenko et al.*, 2000; *Dwyer et al.*, 2004a; *Tsuchiya et al.*, 2007]. X rays are now routinely measured from natural cloud-to-ground and rocket-triggered lightning [*Moore et al.*, 2001; *Dwyer et al.*, 2003, 2004b, 2005a; *Howard et al.*, 2008]. Large bursts of gamma rays emanating from our atmosphere, called terrestrial gamma-ray flashes (TGFs), have been observed by several spacecraft [*Fishman et al.*, 1994; *Smith et al.*, 2005], and long laboratory sparks in air at 1 atmosphere pressure have been found to emit X rays, very similar in characteristics to lightning discharges [*Dwyer et al.*, 2005b; *Rahman et al.*, 2008; *Dwyer et al.*, 2008b; *Nguyen et al.*, 2008]. All of these high-energy emissions are believed to be the result of bremsstrahlung produced by runaway electrons in air [*Gurevich et al.*, 1992; *Gurevich and Zybin*, 2001; *Dwyer*, 2004].

[3] Runaway electrons are produced when the rate of energy gain from strong electric fields exceeds the rate of energy loss, predominantly from ionization energy losses [*Wilson*, 1925]. As long as there is a sufficient potential difference in the high field region, such runaway electrons can gain very large energies, reaching many tens of MeV. As the runaway electrons propagate through air, they occasionally experience hard elastic scattering with atomic electrons in air, resulting in energetic secondary electrons, called "knock-on" electrons, that may also run away in strong electric fields. The result is an avalanche of high-energy electrons that grows exponentially with time and distance, as illustrated in Figure 1 [*Gurevich et al.*, 1992]. This mechanism is called relativistic runaway electron avalanche (RREA) multiplication, sometimes referred to as "runaway breakdown."

[4] Detailed Monte Carlo simulations that contain all of the relevant physics pertaining to runaway electron production and propagation [see *Dwyer*, 2003, 2007] have found that the threshold electric field for producing runaway electron avalanches is $E_{th} = 284$ kV/m × (n/n_o), where n and n_o are the density of air and the density of air at sea level, respectively

[1]Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, Florida, USA.
[2]Physics Department and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, California, USA.
[3]Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA.

0148-0227/10/2009JD012039

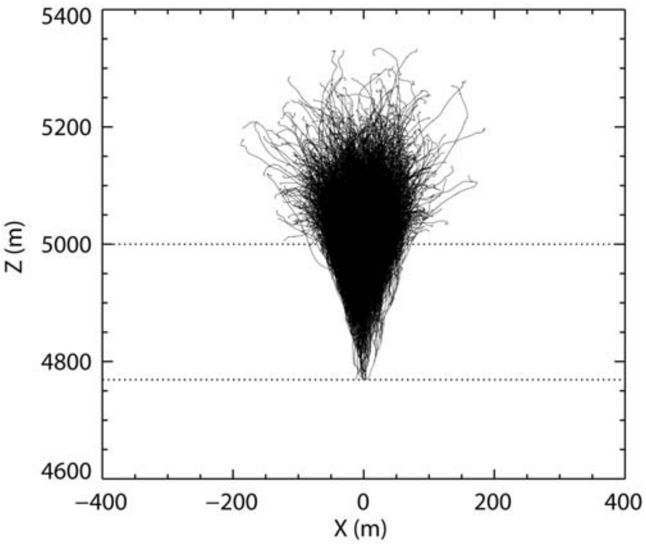

Figure 1. Monte Carlo simulation showing runaway electron trajectories inside a thundercloud at 5-km altitude. The electric field is uniform in the region between the horizontal dotted lines and has a magnitude of 375 kV/m. Above and below the dotted lines, the field is set to zero. The avalanche is initiated by 10 energetic electrons at the bottom of the high-field region, which might correspond to the injection of energetic electrons by a lightning leader. The simulation calculates but does not plot the X rays produced by bremsstrahlung emission. For a realistic thundercloud and lightning, the number of runaway electrons could be 10^{14} times larger than the number shown in the simulation.

[*Dwyer*, 2003]. Electric fields larger than this threshold, which is about ten times smaller than the conventional breakdown field, have been observed inside thunderclouds [*MacGorman and Rust*, 1998; *Marshall and Rust*, 1991; *Marshall et al.*, 2005].

[5] In order to produce a relativistic runaway electron avalanche, by the mechanism described above and illustrated in Figure 1, there must be a source of energetic seed particles, typically with energies above about 100 keV. There are several sources of such seed particles, including secondary particles from cosmic rays, radioactive decays (e.g., radon and its daughter products) and a positive feedback effect caused by backward propagating X rays and positrons (relativistic feedback) [*Dwyer*, 2003, 2007, 2008]. In addition, lightning leaders are capable of accelerating electrons out of the bulk-thermal populations to high enough energies to effectively serve as seed particles for subsequent relativistic runaway electron avalanche multiplication [*Moss et al.*, 2006]. How leaders produce such energetic electrons is still not understood, but the process most likely involves the acceleration of electrons under the influence of very strong electric fields, much greater than the conventional breakdown field.

[6] The runaway electron avalanche *e*-folding length, λ, depends upon the electric field strength and the density of air. For example, for a field of 200 kV/m at an altitude of 5 km (i.e., 400 kV/m normalized to STP), the avalanche length is $\lambda \sim 100$ m [*Dwyer*, 2003; *Coleman and Dwyer*, 2006]. Because the high-field regions inside thunderclouds can extend for many kilometers, very large avalanche multiplication factors may occur.

[7] Until recently, it has been difficult to estimate the radiation dose that an individual would receive if exposed to the runaway electrons that are present inside or near thunderclouds. However, recent advances in X-ray/gamma-ray observations from thunderclouds and lightning along with advances in theory and modeling now allow an estimate of such doses. Specifically, in this paper, we will use Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) TGF observations and modeling, X-ray measurements of lightning using the Thunderstorm Energetic Radiation Array (TERA) at the University of Florida/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, detailed Monte Carlo simulations of runaway electron avalanches, and limits on the runaway electron fluence (time integrated flux) resulting from relativistic feedback to estimate the effective dose that a passenger inside an aircraft would receive from the runaway electrons produced by a thundercloud. We will show that it is possible that the effective dose can sometimes reach biologically significant levels.

2. Observations

[8] In this paper, we shall use two recent observations of X-ray/gamma-ray emissions from thunderclouds and lightning that allow the total number of runaway electrons to be quantitatively estimated: RHESSI TGF observations and X-ray observations of lightning, which are summarized in the following sections.

2.1. RHESSI Terrestrial Gamma-Ray Flash (TGF) Observations

[9] Terrestrial gamma-ray flashes (TGFs) are intense bursts of high-energy gamma rays, observed from space, that emanate from the Earth's atmosphere. They were discovered in 1994 using the Compton Gamma-Ray Observatory Burst And Transient Source Experiment (CGRO/BATSE) instrument [*Fishman et al.*, 1994]. Figure 2 shows an example of one such TGF (event 106) as measured by BATSE (http://www.batse.msfc.nasa.gov/batse/tgf/). Even though these measurements were made several hundred kilometers above the Earth's atmosphere, the TGF is still intense enough that significant instrumental dead-time is occurring in the event due to the high count rates [*Grefenstette et al.*, 2008]. As can be seen, the TGF clearly stands out from the background, which in addition to other background sources includes the contribution of all energetic particles generated in more than a million square kilometers of atmosphere below the spacecraft.

[10] Recently, the RHESSI spacecraft has made very detailed observations of the intensity and average energy spectrum of TGFs [*Smith et al.*, 2005], making it possible to infer the source altitudes based upon how the bremsstrahlung spectrum is modified as the gamma rays propagate through the atmosphere. *Dwyer and Smith* [2005] fit the results of Monte Carlo simulations, which included the runaway electron avalanches, the associated bremsstrahlung emission, the gamma-ray propagation through the atmosphere and the instrument response, to the RHESSI TGF

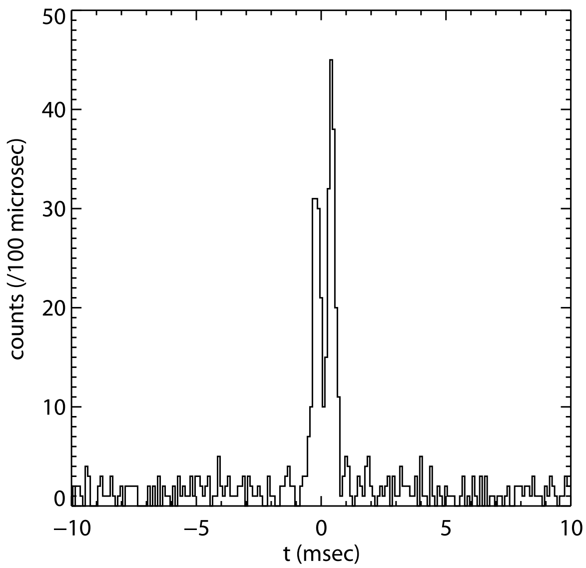

Figure 2. CGRO/BATSE terrestrial gamma-ray flash (TGF) event 106 showing counts/100 ms for gamma-ray energies above 25 keV. The background counts include the gamma-ray emission from more than a million kilometers of atmosphere. In contrast, the TGF, which markedly exceeds the background, may originate from a region just a few hundred meters across. Adapted from http://www.batse.msfc.nasa.gov/batse/tgf/BATSE. Data courtesy of G. J. Fishman.

average spectrum. They found that TGFs did not originate from typical sprite altitudes as was previously assumed, but instead originate from much deeper in the atmosphere in the altitude range of ~15–21 km [see also *Dwyer et al.*, 2008a; *Grefenstette et al.*, 2008; *Carlson et al.*, 2007; *Østgaard et al.*, 2008]. When including the location of the spacecraft relative to the TGF source, *Hazelton et al.* [2009] found that a 15 km source altitude was the most consistent with the RHESSI data. Note that for a source altitude at 15 km or lower, in order to fit the RHESSI spectrum, the emission must be roughly isotropic into an upward pointing cone with a half angle of about 45°. A beamed source, on the other hand, requires a higher source altitude, i.e., ~20 km, to fit the RHESSI data. These low-altitude sources are consistent with the tops of thunderclouds at low geographic latitudes where most TGFs are observed [*Williams et al.*, 2006] and are supported by sferics observations of *Cummer et al.* [2005] and *Stanley et al.* [2006]. In the latter paper, Stanley et al. found that for two events the lightning originated from 13.6 km and 11.5 km. Generally speaking, because both the gamma-ray production and lightning initiation are likely to occur in regions of the thunderstorm with large values of E/n, where E is the magnitude of the electric field and n is the air density, it is plausible that the source altitudes of those TGFs were also near 13.6 and 11.5 km, respectively—altitudes where aircraft routinely fly.

[11] More conservatively, if we take a 15 km source as the most likely altitude for RHESSI TGFs, then detailed Monte Carlo simulations have shown that in order to account for the flux of gamma rays seen at 600 km altitude by RHESSI the average number of high-energy, runaway electrons must be at least 10^{17} at the source [*Dwyer and Smith*, 2005]. Although details of the source region are not known, this estimation is based primarily upon gamma-ray scattering cross sections, which are very well known. Furthermore, some TGFs are observed to be more intense than the average by at least a factor of two. As a result, we shall take 2×10^{17} as a reasonable number of runaway electrons in a bright TGF. Indeed, the real number could be larger, since it is now known that RHESSI is saturating during many intense TGF events [*Grefenstette et al.*, 2009]. A similar instrumental saturation was reported to occur during CGRO BATSE TGFs [*Grefenstette et al.*, 2008]. It should be pointed out that although 15 km may be representative of the TGFs observed by RHESSI, this does not mean that 15 km is the average altitude of TGFs. Since RHESSI is not likely to detect TGFs originating from deeper in the atmosphere due to rapid attenuation of the gamma rays in air, the average depth of these gamma-ray sources may in fact be much lower. This is also supported by the fact that the altitude range of the largest electric fields seen inside thunderclouds is usually lower, more on a par with commercial aircraft altitudes. Finally, *Dwyer et al.* [2004a] reported a bright gamma-ray flash measured on the ground originating from an overhead thundercloud. This gamma-ray flash had a similar energy spectrum and duration to TGFs, suggesting that TGF-like events may occur lower in the thunderclouds as well.

2.2. X-Ray Observations of Lightning

[12] The Thunderstorm Energetic Radiation Array (TERA) at the ICLRT is a large array of 24 X-ray instruments covering the 1 km^2 facility, centered on the rocket launch tower that allows lightning to be artificially triggered. This array has measured X rays from many natural and triggered lightning flashes. *Saleh et al.* [2009] analyzed the X-ray data from a descending dart-stepped leader associated with one such triggered lightning flash and used Monte Carlo simulations to calculate the number of energetic electrons emitted by the dart-stepped leader. These simulations included the detector responses, the propagation of the X rays through air, interactions of the X rays with the ground and the propagation and bremsstrahlung emission of energetic electrons. Figure 3, from *Saleh et al.* [2009], shows the raw data from the sodium iodide photomultiplier tube (NaI/PMT) detectors, at several distances, for this event along with electric field and current data. It was found that the characteristic energy of the energetic electrons for this leader was 1 MeV. The best fit energetic electron luminosity (electrons per second) of the triggered lightning dart-stepped leader was found to be 3×10^{16} s^{-1} just before the leader reached the ground [*Saleh et al.*, 2009].

[13] Both dart leader and stepped leader X-ray emission arrive in short (<1 μs) bursts. In stepped leaders, these bursts are found to be associated with the step formation. For the dart leader emission, it is not clear if the X rays are also associated with leader steps. However, the X-ray emission from dart leaders, dart-stepped leaders and stepped leaders appear to be very similar [*Dwyer et al.*, 2005a]. We also note that during the time interval immediately before the start of the return stroke, the measured electric field changes are very complicated and so it is not clear if these field changes, which make copious X rays, should be called leader steps.

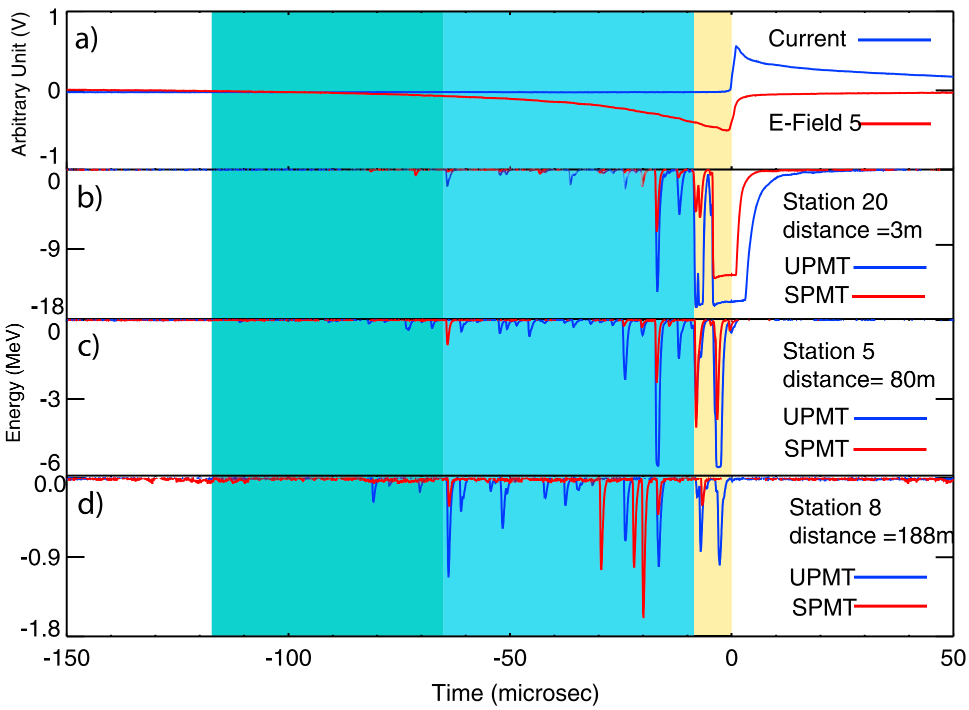

Figure 3. X rays from rocket-triggered lightning [from *Saleh et al.*, 2009]. (a) Lightning current and electric field. (b–c) Waveforms from different X-ray detectors located at 3, 80, and 188 m from the lightning channel. In the plots, each negative pulse is due to a burst of many X rays. The blue traces labeled "UPMT" are the anode signals from NaI/PMTs contained within a 0.32 cm thick aluminum box. The red traces labeled "SPMT" are the anode signals from NaI/PMTs contained within a 0.3 cm thick aluminum box and also completely shielded by 0.32 cm thick lead. Because the lead attenuates X rays below about 200 keV, the relative intensities of the blue and red traces provides information about the energy spectra of the X rays. Both shielded and unshielded detectors at each station are shown on the same plot. The return stroke is at time $t = 0$ in these plots.

[14] The energetic electron luminosity of 3×10^{16} s^{-1} reported by Saleh et al. was the average over the last 7 μs before the return stroke (indicated by the yellow region Figure 3), so the leader emitted about 2×10^{11} energetic electrons during that time period. Using the leader propagation speed of 4.8×10^6 m/s measured for this same event by *Howard et al.* [2008], the leader emits about 6×10^9 energetic electrons per meter. Because the X-ray emission is not continuous, but instead arrives in short <1 μs long pulses as the leader propagates, the peak luminosity within that 7 μs time period was much larger than the average luminosity of 3×10^{16} s^{-1}. For instance, because there were 1 to 2 X-ray pulses emitted during that time period, there are about 10^{11} energetic electrons per pulse, and presumably per step. Measurements by TERA have found that natural lightning stepped leaders are almost always much more intense in X rays than triggered (and natural) lightning dart or dart-stepped leaders, suggesting that this number of seed electrons is probably on the low side for natural lightning.

[15] The 1 MeV characteristic energy for the energetic electrons, determined by *Saleh et al.* [2009], is much lower than the 7.3 MeV average energy for runaway electrons during relativistic runaway electron avalanche (RREA) multiplication, indicating that very little if any additional avalanche multiplication is occurring after the energetic electrons are generated by the lightning. However, if instead, the leader occurred in a region inside a thundercloud in which the ambient electric field was greater than the runaway electron avalanche threshold, then these energetic electrons would serve as seeds for relativistic runaway electron avalanches. Observations of triggered lightning show that the luminosity increases as the leader approaches the ground [*Saleh et al.*, 2009]. One explanation is that the enhancement in the electric field due to the image charge from the leader increases the number and/or energy of the runaway electron produced by the leader. If this is the case, then an even larger numbers of energetic seed electrons from leaders propagating within the high-field regions of a thundercloud might be expected.

[16] Based upon X-ray measurements made near the ground, one leader step usually produces the energetic electrons in less than about 1 μs. As a result, the duration of the runaway electron avalanche could also be less than about 1 μs. In the calculations that follow, we could use 10^{11} as the number of seed electrons injected by lightning from just one leader step. However, in reality, many leader steps from multiple branches may occur in the avalanche region. For instance, within the first runaway electron avalanche length of 100 m (corresponding to 200 kV/m at 5 km) 6×10^{11} energetic seed electrons would be injected by the lightning leader when using 6×10^9 electrons per meter as calculated above. For the calculations that follow, we shall use 6×10^{11}

energetic electrons for the number of seed particles injected into the runaway electron avalanche region. For the dart-stepped leader discussed earlier, these electrons would be injected in about 20 μs at 5 km. However, at 15 km, the avalanche length for the same sea level equivalent field is about 4 times longer, giving a duration of about 75 μs, which is similar to the timescale for the shortest TGFs. In addition, using a slower propagation speed more appropriate for stepped leader, 10^6 m/s, gives a 400 μs pulse width, which is more typical for TGFs. As a result, the time variations observed for TGFs are consistent with the range of speeds observed for leader propagation, according to this model.

3. Radiation Dose Calculations

3.1. Overview

[17] Given the fluence (number per meter squared) and energy spectrum of the runaway electrons, there are several ways of calculating the dose. In SI units, the absorbed dose, which is the energy absorbed per unit mass, has units of gray (Gy) = 100 rad. In terms of hazards to living organisms, the dose equivalent is often used. The dose equivalent is obtained from the absorbed dose by multiplying by a quality factor, Q, for the type of radiation present. For X rays, gamma rays and energetic electrons, $Q = 1$. The SI units of the dose equivalent is the sievert (Sv) = 100 rem [*Knoll*, 2000].

[18] The average energy of runaway electrons is 7.3 MeV, independent of the electric field magnitude and the air density [*Dwyer*, 2004]. The energy spectrum of the runaway electrons is approximately exponential with an e-folding energy of 7.3 MeV [*Lehtinen et al.*, 1999]. Because most of these electrons are minimum ionizing, they will lose energy at a rate of 1.87 MeV/cm in human soft tissue. Therefore, the majority of runaway electrons that strike a human body will be absorbed within the body. Because the runaway electrons will be produced with a lateral distribution measuring from tens to hundreds of meters across, an individual exposed to the runaway electrons will be struck by an approximately uniform flux from one direction depending upon the orientation of the thundercloud electric field, which is not necessarily vertical.

[19] If for simplicity we consider the anteroposterior (AP or front-to-back) direction, then the whole body dose equivalent can be found as follows:

$$H = (QK_{\rm ave}A/M)\Phi_{\rm re} = h\Phi_{\rm re}, \qquad (1)$$

where $Q = 1$ is the quality factor for energetic electrons, and $K_{\rm ave} = 7.3 \times 10^6$ eV, i.e., 1.2×10^{-12} J, is the average energy of the runaway electrons. Here, $\Phi_{\rm re}$ is the runaway electron fluence; A is the cross-sectional area of an individual exposed to the radiation, and M is their mass. The constant h is the conversion factor that takes us from fluence to dose equivalent. Using $A = 0.5$ m^2 and $M = 75$ kg, equation (1) gives $h \sim 8 \times 10^{-15}$ Sv m^2.

[20] Because an individual exposed to the runaway electrons inside a thundercloud would most likely be inside an aircraft, we shall include the attenuation due to the electrons passing through an aluminum aircraft skin as follows. The electrons are minimum ionizing and so will lose on average about 2.3 MeV passing through 0.25 inches (0.64 cm) of aluminum. Because the energy spectrum is exponential, reducing all the electron energies by this amount does not change the shape of the energy spectrum. Instead, the fluence of the runaway electrons is reduced by about 27%. Including the aircraft skin in this manner results in $h \sim 6 \times 10^{-15}$ Sv m^2, which gives the dose from an incident fluence of runaway electrons measured just outside the aircraft.

[21] To verify this calculation, a full GEANT simulation [*CERN Application Software Group*, 1993] was performed using a spherical aluminum aircraft shell (radius = 2 m) with a cylindrical water target placed inside. The target was a cylinder of water 1.8 m long and 0.115 m in radius (mass = 75 kg). For the simulations, realistic runaway electron and photon energy distributions were used, calculated from detailed Monte Carlo simulations [*Dwyer*, 2003, 2004, 2007, 2008; *Dwyer and Smith*, 2005]. The amount of deposited energy inside the water target was found, allowing the conversion factor between fluence and whole body dose equivalent, h, to be determined. For example, for a 0.5 cm thick aluminum skin, it was found that $h \sim 4 \times 10^{-15}$ Sv m^2 for the energetic electrons and $h \sim 3 \times 10^{-16}$ Sv m^2 for the energetic photons. This result for the electrons, which did not include the weighting factors for the tissues and organs of the body, agrees well with the calculations above.

[22] A more rigorous calculation involves performing a Monte Carlo simulation using a realistic model of human tissue including the appropriate weighting factors for all the tissues and organs of the body. The result is called the effective dose and is a more meaningful quantity in terms of assessing radiation risks [*Shapiro*, 2002].

[23] The equation for the effective dose is

$$E = h_E\Phi_{\rm re}. \qquad (2)$$

The conversion factor increases rapidly with energy with $h_E \sim 4 \times 10^{-16}$ Sv m^2 at 1 MeV, reaching $\sim 3 \times 10^{-14}$ Sv m^2 above 30 MeV (AP direction) [*Katagiri et al.*, 2000; *Pelliccioni*, 2000].

[24] Weighting the conversion factors with the TGF energetic electron spectrum gives $h_E \sim 9 \times 10^{-15}$ Sv m^2 (AP direction). Interestingly, this conversion factor is almost the same value calculated for the whole body dose equivalent above. Taking into account the effects of the aircraft material, the conversion factor is reduced slightly to $h_E \sim 7 \times 10^{-15}$ Sv m^2, which gives the effective dose from the fluence of runaway electron measured just outside the aircraft. This is the number that we shall use throughout the remainder of this paper for the doses from energetic electrons inside a thundercloud.

[25] Simulations show that for each runaway electron 1.6 X rays/gamma rays exit the TGF source region. For X rays and gamma rays, the conversion factor for effective dose is in the range $h_E \sim 3.7 \times 10^{-17}$ Sv m^2 at 50 keV increasing to 5.2×10^{-15} Sv m^2 at 50 MeV (AP direction), which is smaller than for electrons due to the longer interaction lengths of the photons [*Knoll*, 2000; *Pelliccioni*, 2000]. Using a lower cutoff at 50 keV to take into account the absorption in the aluminum aircraft skin and weighting the conversion factors with the TGF X-ray source spectrum gives $h_E \sim 3 \times 10^{-16}$ Sv m^2 (AP direction). When including

the factor of 1.6, we find that the effective dose for X rays and gamma rays emitted by the runaway electron avalanches is about a factor of 15 smaller than for the runaway electrons directly. On the other hand, the X rays and gamma rays propagate much farther distances through air than the electrons, so the probability of receiving some dose from the X rays and gamma rays is greater.

3.2. Doses Related to Lightning

[26] Let us first estimate the dose received from the energetic electrons from a direct lightning strike near the ground. Because the energetic electrons do not travel far through air, it seems reasonable to include only the electrons from one leader step. In this case, as discussed above, about 10^{11} energetic electrons with an average energy of 1 MeV are produced. It is currently not known over what spatial extent these electrons are produced other than they are spatially associated with the leader step formation process. Nevertheless, let us consider two cases for the radius of the energetic electron beam: $r = 1$ m and $r = 10$ m. The latter is a reasonable upper limit since this corresponds to the approximate length of one leader step near the ground. For an exponential electron spectrum with a characteristic energy of 1 MeV, the conversion factor is $h_E \sim 7 \times 10^{-16}$ Sv m^2 (AP direction) [*Katagiri et al.*, 2000]. This gives the effective dose of 2×10^{-5} Sv and 2×10^{-7} Sv, for $r = 1$ m and $r = 10$ m, respectively, neither of which is a significant dose [also see *Whitmire*, 1979].

[27] According to *Saleh et al.* [2009], for the same triggered lightning event the peak X-ray luminosity was 4×10^{15}/s. This luminosity is smaller than the electron luminosity due to short path length of 1 MeV electrons in air (few meters) and the low efficiency for electrons to make bremsstrahlung radiation at these energies. Because the average X-ray energy in this case is a couple of hundred keV, they are much more penetrating than the electrons, requiring more mass to deposit the same energy. Using an estimate of the bremsstrahlung X-ray spectrum for lightning gives $h_E \sim 1 \times 10^{-16}$ Sv m^2 (AP direction). As a result, the dose from the X rays should be much smaller than for the electrons by at least an order of magnitude.

[28] To calculate the fluence of runaway electrons that result from a lightning leader inside or near a thundercloud, when runaway electron avalanche multiplication is occurring, we need to know two additional pieces of information: the first is the avalanche multiplication factor and the second is the size of the runaway electron beam as it exits the avalanche region. For the latter, as can be seen in Figure 1, as runaway electrons propagate through air, elastic scattering causes a lateral diffusion that results in a spreading in the avalanche. On the other hand, if the electric field lines converge at the end of the avalanche region where the positive charge center is located, then the runaway electron beam would also converge and the lateral radius will be reduced. Because the electric field configuration is not known, we shall leave the radius of the runaway electron beam as a variable in the calculations.

[29] The runaway electron multiplication factor is strongly constrained by the relativistic feedback mechanism, which includes positron feedback and X-ray feedback [*Dwyer*, 2003, 2007, 2008]. As the avalanche multiplication factor is increased, the number of backward propagating runaway positrons and backward Compton scattered X rays also increases. Because the backward propagating positrons and X rays can produce additional energetic seed electrons near the start of the avalanche region (with the most negative electric potential), these particles cause a positive feedback effect with more and more avalanches being produced. Indeed, with this mechanism, the production of energetic runaway electrons can become self-sustaining, with no additional external seed particles required. In this case, the large number of runaway electrons produced and the amount of ionization generated quickly reduces the electric field, thereby reducing the avalanche multiplication factor. Monte Carlo simulations show that although the exact value of the maximum avalanche multiplication factor depends upon the electric field configuration, it generally is less than 10^5 in most cases that are likely to occur inside thunderclouds [*Dwyer*, 2008]. As a result, we shall use 10^5 as the multiplication factor for the calculations in this paper, corresponding to 11.5 avalanche lengths. As an example, a field of 200 kV/m, extending over 1.3 km, at an altitude of about 5 km would result in this avalanche multiplication factor. The potential difference in this case is 260 MV. Such a scenario is not unreasonable for thunderclouds, which have large electric fields and dimensions of many tens of kilometers. We note that a multiplication factor of 10^5 is currently a theoretical limit and has not yet been established observationally. Furthermore, this limit may be circumvented if the electric field is increased very rapidly, on a timescale less than a few hundred microseconds [*Dwyer*, 2007]. This may occur if lightning rapidly rearranges the charge inside the thundercloud, enhancing it in some regions. Such field enhancements are known to happen in the space above thunderclouds where sprites and other transient-luminous events (TLEs) are produced. In other words, an aircraft need not be inside the thundercloud in order to be in a runaway electron avalanche region.

[30] Figure 4 shows the effective dose received by an individual in an aircraft (shielded by 0.25 inches of aircraft aluminum) versus the source diameter if the aircraft were struck by the most intense part of the runaway electron beam initiated by one lightning leader step, assuming a 10^5 multiplication factor. In this figure, the fluence of runway electrons [in number/m^2] is $\Phi_{re} = 6 \times 10^{11} \times 10^5/(\pi r^2)$, where r is the radius of the runaway electron beam at the end of the avalanche region (note this is different from the size of the seed electron source at the start of the avalanche region). The effective dose was then calculated using equation (2), i.e., multiplying by 7.0×10^{-15} Sv m^2. Although it is not known how small the source region can be, in Figure 4, we shall only plot the doses for source diameters larger than 50 m (the rough size of a stepped leader step well above the ground), keeping in mind that a smaller source region will produce a larger dose. As discussed above, the fluence of the X rays and gamma rays at the source is about 1.6 times larger than the electrons, but the conversion factor to dose is much smaller, resulting in a smaller effective dose from the photons. In the figure, the horizontal dashed lines show the radiation doses that are the whole body limit for members of the public (labeled regulatory limit), and the dose that would result in mild radiation sickness. Note that the dose that would result in death for approximately 50% of the individuals is a few Sv [*Shapiro*,

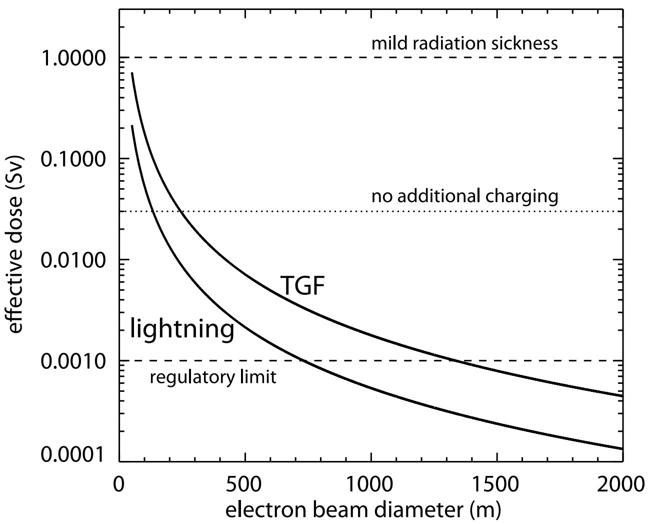

Figure 4. The effective dose produced by one lightning leader inside a thundercloud and a TGF versus the diameter of the energetic electron beam. The curve labeled "lightning" is the effective dose for a lightning leader with an avalanche multiplication factor of 10^5. The curve labeled "TGF" is the effective dose for a TGF event with 2×10^{17} runaway electrons. Note that the TGF fluence (and dose) is close to lightning leader fluence (and dose), suggesting a link between these two phenomena. The horizontal dotted line is the maximum dose that could be received under the assumption that the energetic electrons promptly discharge the electric field, stopping the runaway electron production, with no additional charging processes occurring. The horizontal dashed lines show the maximum dose permitted for the general population (labeled "regulatory limit") and the dose in which mild radiation sickness would occur.

2002]. The dose shown in Figure 4 from lightning could be received in less than 1 μs.

3.3. Doses From TGFs

[31] Switching our attention to terrestrial gamma-ray flashes, in order to calculate the radiation dose that could be received from a TGF at its source, the lateral extent of the runaway electron region must be assumed. Figure 4 shows the effective dose that would result if an aircraft was located near the end of the avalanche region during a TGF versus the diameter of the end of the TGF source region, i.e., the diameter of the runaway electron beam at the end of the avalanche region. In this calculation, the fluence of runaway electrons is estimated from RHESSI to be $\Phi_{re} = 2.0 \times 10^{17}/(\pi r^2)$, as discussed above. As can be seen in Figure 4, the effective dose from the energetic electrons in a TGF can potentially be large for small electron beam diameters. The dose shown in Figure 4 from a TGF would typically be received in less than a few 100 μs.

[32] BATSE data can be used to obtain an independent estimate of the TGF source radius. *Nemiroff et al.* [1997] found that TGFs exhibit intensity fluctuations on timescales as small as 26 microseconds. This timescale limits the possible size of the TGF source region. For example, *Dwyer* [2008] suggested that lightning leaders acting as seeds for additional avalanche multiplication may produce TGFs. If lightning leaders are involved in the production of the TGF gamma rays, then using the dart-stepped leader propagation speed of $v_l = 4.8 \times 10^6$ m/s, measured by *Howard et al.* [2008] and used by *Saleh et al.* [2009] in their analysis, the maximum distance that a signal could propagate in order to produce an intensity change is just 125 m, which can be used as an estimate of the radius of the source region [*Dwyer*, 2008]. In other words, if TGFs are indeed produced by a lightning leader in a high-field region, then the smaller source region sizes appearing on the left side of Figure 4 may be most likely.

[33] It may not be a coincidence that the TGF fluence and the lightning fluence and hence the doses are nearly the same. The fluence for the TGF shown in Figure 4, which corresponds to the upper end measured by RHESSI, is only a factor of 3 larger than that predicted for a single leader propagating inside a thundercloud. If we had instead used the average RHESSI TGF fluence, then the TGF and lightning curves shown in Figure 4 would be the same. This work is a quantitative calculation that demonstrates that one lightning leader propagating through a modest thundercloud electric field, within the limits set by relativistic feedback, can account for the TGF fluence. As a result, the X-ray phenomena measured on the ground and the gamma-ray emission seen from space may be closely related.

3.4. Doses From the Runaway Electrons From the Cosmic Ray Background

[34] Because atmospheric cosmic ray particles are always present inside thunderclouds and seed the runaway electron avalanches at a rate of about 10^4 m^{-2} s^{-1}, the flux of runaway electrons at the end of the avalanche region from this steady state cosmic ray background will be 10^9 m^{-2} s^{-1} for a 10^5 avalanche multiplication factor. As a result, this will produce an effective dose of about 10^{-5} Sv/s in at the end of the avalanche region. *Tsuchiya et al.* [2007], studying winter thunderstorms in Japan from the ground, reported gamma-ray emission that lasted up to 40 s and had energies up to 10 MeV. The duration of this emission is substantially longer than the millisecond-long emission observed from lightning and terrestrial gamma-ray flashes. The timescale observed is more reminiscent of the in situ X-ray enhancements observed of *Eack et al.* [1996], which lasted about 1 min and those observed by *McCarthy and Parks* [1985] and *Parks et al.* [1981], which lasted for up to 20 s. Because of their long duration, these "surges" in the gamma-ray count rates may be the result of this steady state emission. On the other hand, the large amount of ionization produced by the energetic runaway electrons, initiated, for example, by atmospheric cosmic rays, will increase the conductivity in the avalanche region to a point at which the electric field will slowly discharge. For 11.5 avalanche lengths, without active charging of the thundercloud, the field would be reduced by 1/*e* in about 0.2 s from seeds provided by the ambient cosmic ray flux. However, with active thundercloud charging, it may be possible to maintain the field and the avalanche multiplication for an extended time.

[35] If we take 1 min as a characteristic timescale for the avalanche region to remain charged, producing runaway electrons, then a maximum dose of 6×10^{-4} Sv would be received by an individual in an aircraft, assuming that the

aircraft could somehow remain in the high-field region for so long. In short, it does not appear that the steady state runaway electron production from ambient cosmic rays will produce a significant dose. If, on the other hand, a cosmic ray extensive air shower happened to traverse the high-field region at precisely the time that the aircraft was at the end of the avalanche region, then a larger dose is possible. However, in order to produce the same number of seed particles as a single lightning leader step, an air shower with an energy of almost 10^{21} eV would be required. Such an ultra-high-energy air shower is extremely rare and would be among the most energetic ever observed. For instance, the flux of air showers above 10^{20} eV is only about 1 km^{-2} sr^{-1} $century^{-1}$ [*Longair*, 1992].

3.5. Limit on the Dose Set by the Discharge Current

[36] One potential limit on the dose is due to the large discharge current produced by the runaway electron beam and the accompanying low-energy electrons and ions caused by ionization of the air. *Dwyer* [2008] calculated the current for TGFs and found that the largest contribution came from the drifting ions. At 5 km, 2 × 10^{17} runaway electrons would generate a peak current of about 10 kA. This current will quickly discharge the electric field, eventually stopping the runaway electron production, if no additional charge transfer, such as from lightning, is occurring. This, in turn, could limit the dose. For a very short burst of runaway electron, lasting on the order of microseconds, using a one-dimensional plane geometry, the maximum dose is about 0.03 Sv at 5 km and scales approximately linearly with the air density. This limit is plotted as horizontal dotted line in Figure 4.

[37] A calculation of the discharge current generated by the relativistic feedback mechanism gives a similar maximum dose, produced when the runaway discharge becomes self-sustaining. *Dwyer* [2008] calculated the size of the TGF source region for the relativistic feedback mechanism and found that the diameter could be as little as a few hundred meters for this mechanism at an altitude of 15 km [see also *Dwyer*, 2003, 2005, 2007], which is reasonable for the size of the highest electric field region inside a thundercloud [*Rakov and Uman*, 2003]. At lower altitudes, due to the scaling of particle interaction lengths with the inverse of the air density and the scaling of the electric field with density, the corresponding doses could be larger. For example, at 5 km altitude the effective dose based upon the relativistic feedback mechanisms is 0.03 Sv, the same as above. It should be emphasized that the source mechanism for producing TGFs has not yet been settled, and so small source regions that produce large doses cannot be ruled out at this time [*Dwyer*, 2008].

4. Discussion

[38] An important factor in determining the total dose is whether or not the current generated by the bursts of energetic radiation will discharge the electric field. If no additional charging is occurring or the charge transfer is such that the electric field is allowed to relax, then the runaway electron production may cease. More detailed modeling is needed to investigate further the dose that would actually result, since discharging the field in one region may result in an enhanced runaway electron production in another nearby region [see *Dwyer*, 2005]. In addition, if positive charge is being transported to the end of the avalanche region to maintain the electric field, e.g., by lightning, then the high-energy radiation could continue and very large doses could be delivered. As discussed above, a TGF with 2 × 10^{17} electrons will produce a discharge current of approximately 10 kA, which is similar in value to a lightning current, so this scenario is not unreasonable.

[39] The second important factor is the size of the runaway electron beam, which at present is not known. *Dwyer* [2008] outlined how the TGF source radius could be determined using remote measurements of the current and charge moment changes using sferics observations associate with TGFs. More in situ observations will also be important.

[40] An obvious question is how probable is it for an aircraft to be in a region in or near a thundercloud such that a large radiation dose is delivered to individuals onboard. Aircraft are easily capable of penetrating into high–electric field regions, at or above the runaway electron avalanche threshold field [*Rakov and Uman*, 2003]. For instance, using aircraft, *Gunn* [1948] measured fields up to 340 kV/m; *Imyanitov et al.* [1972] measured field up to 250 kV/m; *Fitzgerald* [1984] reported fields of 120 kV/m and *Kasemir and Perkins* [1978] reported fields up to 280 kV/m. For comparison the runaway electron avalanche threshold field is about 150 kV/m at a 5 km altitude. We note that since the measurement of electric field strengths from aircraft may be influenced by the conducting aircraft skin and other disturbances caused by the aircraft's passage, the older quoted numbers, which were acquired before these effects were understood, may be of questionable accuracy [*Mazur et al.*, 1987].

[41] For the largest doses, not only must the aircraft be in or near the high-field region, it also must be there when the runaway electron flux is large, such as may occur during a lightning flash or during a TGF-like event. Since these events only last a fraction of a second, such an event would require the aircraft to be in the wrong place at exactly the wrong time, so to speak. Generally, aircraft try to avoid thunderclouds, but in some cases avoiding the storm may not be possible, as illustrated by the fact that aircraft are commonly struck by lightning, e.g., about 1 to 2 times per year [*Fisher et al.*, 1999].

[42] The majority of aircraft are stuck by lightning while they are inside clouds, often near the altitudes where temperatures are near 0°C [*Plumer et al.*, 1985; *Murooka*, 1992; *Fisher et al.*, 1999]. Electric field measurements made on research aircraft struck by lightning typically show they were flying in ambient fields of about 50 kV/m at 5 km altitude [*Uman and Rakov*, 2003; *Lalande et al.*, 1999], corresponding to about 1/3 the runaway electron avalanche threshold field. Approximately 90% of lightning strikes to aircraft are thought to be initiated by the aircraft itself [*Mazur*, 1989; *Reazer et al.*, 1987]. In such cases, one can imagine a scenario in which an aircraft that is at the end of the runaway electron avalanche region or just outside this high-field region initiates lightning that then propagates to the start of the avalanche region and produces the runaway electron avalanche outlined above.

[43] The remaining ~10% of lightning strikes to aircraft are consistent with natural lightning propagating toward and

Table 1. Dose Comparisons[a]

Source	Duration or Number
Air crew at 10 km (4 μSv/h)	7500 h
General population in New York city from all sources (870 μSv/yr)	35 years
Chest X ray (77 μSv each)	400 repetitions

[a]The dose received by an individual in an aircraft directly struck by a TGF or lightning energetic electrons (0.03 Sv) is roughly equivalent to these exposures. Data are from *Shapiro* [2002].

intercepting the aircraft [*Reazer et al.*, 1987]. For instance, *Moreau et al.* [1992] analyzed electric field waveforms located at different positions on a C-160 aircraft that was struck by lightning and interpreted their data as resulting from the attachment of an approaching negative lightning leader. Because a negative lightning leader will generally follow the same path along the electric field lines as the runaway electrons, the scenario of a negative leader striking an aircraft is the same scenario considered above in Figure 4 and the associated discussion.

[44] On average, each commercial aircraft is struck by lightning about once per 3000 flight hours, or about 1 to 2 times per year [*Fisher et al.*, 1999]. Although there are many unknowns, including the occurrence rate of TGFs relative to lightning, the effect of the aircraft triggering the lightning, and the frequency and lengths of acceleration regions in thunderstorms, considering the number of aircraft in operation around the world and the number of individuals flying, it is possible that a significant number may be at risk of receiving large radiation doses.

[45] To put the amount of radiation produced by a TGF and potentially by lightning in perspective, it is useful to make a comparison with the background rate of atmospheric cosmic rays—the dominate component of energetic particles in our atmosphere. In 1 ms, one TGF event generates more than 3 orders of magnitude more high-energy particles than all the atmospheric cosmic rays striking the entire surface of the planet in that time. Furthermore, this large amount of radiation may be produced in an area the size of a football field. Finally, for comparison, in Table 1 we list the exposures from several common sources that would be required to match that from a thundercloud as outlined in this paper. For simplicity we assume that the quality factors for all cases is 1 in converting absorbed doses to dose equivalents.

5. Summary

[46] In this paper, we have estimated the fluence of high-energy runaway electrons produced by leader emission inside thunderclouds and from terrestrial gamma-ray flashes. We have found that for reasonable runaway electron avalanche multiplication consistent with relativistic feedback limits, the fluence of this lightning generated emission and TGFs agree well, suggesting a potential physical link between the energetic radiation produced by lightning and the gamma-ray emission seen from space. In addition, based upon these inferred fluences, we have estimated that radiation doses that individuals in aircraft could potentially receive from thunderstorms and lightning. Based upon our current understanding of thunderclouds and lightning and runaway electron production in our atmosphere, it is plausible that passengers and crew members in an aircraft could sometimes be exposed to high radiation doses. It should be emphasized that we have presented best estimates based upon our current understanding of the physics of runaway electrons and lightning discharges and based upon existing measurements of thunderclouds, lightning and terrestrial gamma-ray flashes, and that direct measurements of these doses inside thunderclouds have not yet been made. Even if these large doses do exist, the chance that an aircraft is actually exposed to these radiation levels may well be small. However, given the large number of individuals that fly, the risks need to be carefully evaluated. The consequences could be serious enough that further research in this subject is warranted, especially considering that the upper limits on the X-ray/gamma-ray brightness of TGFs and lightning have not been established, so the upper limit in the radiation dose that is possible is not known.

[47] **Acknowledgments.** We wish to thank Jerry Fishman for useful conversations and for his help with the BATSE data and analysis. This work was supported by NSF grant ATM 0607885 and DARPA grant HR0011-08-1-0088.

References

Brunetti, M., S. Cecchini, M. Galli, G. Giovannini, and A. Pagliarin (2000), Gamma-ray bursts of atmospheric origin in the MeV energy range, *Geophys. Res. Lett.*, *27*, 1599–1602, doi:10.1029/2000GL003750.

Carlson, B. E., N. G. Lehtinen, and U. S. Inan (2007), Constraints on terrestrial gamma ray flash production from satellite observation, *Geophys. Res. Lett.*, *34*, L08809, doi:10.1029/2006GL029229.

CERN Application Software Group (1993), GEANT: Detector description and simulation tool, *CERN Program Library Long Writeup W5013*, CERN, Geneva, Switzerland.

Chubenko, A. P., V. P. Antonova, S. Y. Kryukov, V. V. Piskal, M. O. Ptitsyn, A. L. Shepetov, L. I. Vildanova, K. P. Zybin, and A. V. Gurevich (2000), Intense X-ray emission bursts during thunderstorms, *Phys. Lett. A*, *275*, 90–100, doi:10.1016/S0375-9601(00)00502-8.

Coleman, L. M., and J. R. Dwyer (2006), The propagation speed of runaway electron avalanches, *Geophys. Res. Lett.*, *33*, L11810, doi:10.1029/2006GL025863.

Cummer, S. A., Y. Zhai, W. Hu, D. M. Smith, L. I. Lopez, and M. A. Stanley (2005), Measurements and implications of the relationship between lightning and terrestrial gamma ray flashes, *Geophys. Res. Lett.*, *32*, L08811, doi:10.1029/2005GL022778.

Dwyer, J. R. (2003), A fundamental limit on electric fields in air, *Geophys. Res. Lett.*, *30*(20), 2055, doi:10.1029/2003GL017781.

Dwyer, J. R. (2004), Implications of X-ray emission from lightning, *Geophys. Res. Lett.*, *31*, L12102, doi:10.1029/2004GL019795.

Dwyer, J. R. (2005), The initiation of lightning by runaway air breakdown, *Geophys. Res. Lett.*, *32*, L20808, doi:10.1029/2005GL023975.

Dwyer, J. R. (2007), Relativistic breakdown in planetary atmospheres, *Phys. Plasmas*, *14*, 042901, doi:10.1063/1.2709652.

Dwyer, J. R. (2008), Source mechanisms of terrestrial gamma-ray flashes, *J. Geophys. Res.*, *113*, D10103, doi:10.1029/2007JD009248.

Dwyer, J. R., and D. M. Smith (2005), A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations, *Geophys. Res. Lett.*, *32*, L22804, doi:10.1029/2005GL023848.

Dwyer, J. R., et al. (2003), Energetic radiation produced during rocket-triggered lightning, *Science*, *299*, 694–697, doi:10.1126/science.1078940.

Dwyer, J. R., et al. (2004a), A ground level gamma-ray burst observed in association with rocket-triggered lightning, *Geophys. Res. Lett.*, *31*, L05119, doi:10.1029/2003GL018771.

Dwyer, J. R., et al. (2004b), Measurements of X-ray emission from rocket-triggered lightning, *Geophys. Res. Lett.*, *31*, L05118, doi:10.1029/2003GL018770.

Dwyer, J. R., et al. (2005a), X-ray bursts associated with leader steps in cloud-to-ground lightning, *Geophys. Res. Lett.*, *32*, L01803, doi:10.1029/2004GL021782.

Dwyer, J. R., H. K. Rassoul, Z. Saleh, M. A. Uman, J. Jerauld, and J. A. Plumer (2005b), X-ray bursts produced by laboratory sparks in air, *Geophys. Res. Lett.*, *32*, L20809, doi:10.1029/2005GL024027.

Dwyer, J. R., B. W. Grefenstette, and D. M. Smith (2008a), High-energy electron beams launched into space by thunderstorms, *Geophys. Res. Lett.*, *35*, L02815, doi:10.1029/2007GL032430.

Dwyer, J. R., Z. Saleh, H. K. Rassoul, D. Concha, M. Rahman, V. Cooray, J. Jerauld, M. A. Uman, and V. A. Rakov (2008b), A study of X-ray emission from laboratory sparks in air at atmospheric pressure, *J. Geophys. Res.*, *113*, D23207, doi:10.1029/2008JD010315.

Eack, K. B., W. H. Beasley, W. D. Rust, T. C. Marshall, and M. Stolzenburg (1996), X-ray pulses observed above a mesoscale convection system, *Geophys. Res. Lett.*, *23*, 2915–2918, doi:10.1029/96GL02570.

Fisher, F. A., J. A. Plumer, and R. A. Perala (1999), *Lightning Protection of Aircraft*, Lightning Technol., Pittsfield, Mass.

Fishman, G. J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *264*, 1313–1316, doi:10.1126/science.264.5163.1313.

Fitzgerald, D. R. (1984), Electric filed structure of large thunderstorm complexes in the vicinity of Cape Canaveral, paper presented at 7th International Conference on Atmospheric Electricity, Am. Meteorol. Soc., Albany, N. Y.

Grefenstette, B. W., D. M. Smith, J. R. Dwyer, and G. J. Fishman (2008), Time evolution of terrestrial gamma ray flashes, *Geophys. Res. Lett.*, *35*, L06802, doi:10.1029/2007GL032922.

Grefenstette, B. W., D. M. Smith, B. J. Hazelton, and L. I. Lopez (2009), First RHESSI Terrestrial gamma ray flash catalog, *J. Geophys. Res.*, *114*, A02314, doi:10.1029/2008JA013721.

Gunn, R. (1948), Electric field intensity inside of natural clouds, *J. Appl. Phys.*, *19*, 481–484, doi:10.1063/1.1698159.

Gurevich, A. V., and K. P. Zybin (2001), Runaway breakdown and electric discharges in thunderstorms, *Phys. Uspekhi*, *44*, 1119, doi:10.1070/PU2001v044n11ABEH000939.

Gurevich, A. V., G. M. Milikh, and R. A. Roussel-Dupré (1992), Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Phys. Lett. A*, *165*, 463–468, doi:10.1016/0375-9601(92)90348-P.

Hazelton, B. J., B. W. Grefenstette, D. M. Smith, J. R. Dwyer, X.-M. Shao, S. A. Cummer, T. Chronis, E. H. Lay, and R. H. Holzworth (2009), Spectral dependence of terrestrial gamma-ray flashes on source distance, *Geophys. Res. Lett.*, *36*, L01108, doi:10.1029/2008GL035906.

Howard, J., M. A. Uman, J. R. Dwyer, D. Hill, C. Biagi, Z. Saleh, J. Jerauld, and H. K. Rassoul (2008), Co-location of lightning leader X-ray and electric field change sources, *Geophys. Res. Lett.*, *35*, L13817, doi:10.1029/2008GL034134.

Imyanitov, I. M., Y. V. Chubarian, and Y. M. Shvarts (1972), Electricity in clouds, translated from Russian, *NASA TT-F-718*, 92 pp., NASA, Washington, D. C.

Kasemir, H. W., and F. Perkins (1978), Lightning trigger field of the Orbiter, final report, NOAA, Silver Spring, Md.

Katagiri, M., M. Hikoji, M. Kitaichi, S. Sawamura, and Y. Aoki (2000), Effective doses and organ doses per unit fluence calculated for monoenergetic 0.1 MeV to 100 MeV electrons by the MIRD-5 phantom, *Radiat. Protect. Dosimetry*, *90*, 393–401.

Knoll, G. F. (2000), *Radiation Detection and Measurement*, 3rd ed., John Wiley, Hoboken, N. J.

Lehtinen, N. G., T. F. Bell, and U. S. Inan (1999), Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes, *J. Geophys. Res.*, *104*, 24,699–24,712, doi:10.1029/1999JA900335.

Lalande, P., A. Bondiou-Clergerie, and P. Laroche (1999), Studying aircraft lightning strikes, *Aerosp. Eng.*, *19*, 39–42.

Longair, M. S. (1992), *High Energy Astrophysics*, vol. 1, 2nd ed., 292 pp., Cambridge Univ. Press, Cambridge, U. K.

MacGorman, D. R., and W. D. Rust (1998), *The Electrical Nature of Storms*, Oxford Univ. Press, New York.

Marshall, T. C., and W. D. Rust (1991), Electric field soundings through thunderstorms, *J. Geophys. Res.*, *96*, 22,297–22,306, doi:10.1029/91JD02486.

Marshall, T. C., M. Stolzenburg, C. R. Maggio, L. M. Coleman, P. R. Krehbiel, T. Hamlin, R. J. Thomas, and W. Rison (2005), Observed electric fields associated with lightning initiation, *Geophys. Res. Lett.*, *32*, L03813, doi:10.1029/2004GL021802.

Mazur, V., L. H. Ruhnke, and T. Rudolph (1987), Effect of E-field mill location on accuracy of electric field measurements with instrumented airplane, *J. Geophys. Res.*, *92*, 12,013–12,019, doi:10.1029/JD092iD10p12013.

Mazur, V. A. (1989), A physical model of lightning initiation on aircraft in thunderstorms, *J. Geophys. Res.*, *94*, 3326–3340, doi:10.1029/JD094iD03p03326.

McCarthy, M., and G. K. Parks (1985), Further observations of X-rays inside thunderstorms, *Geophys. Res. Lett.*, *12*, 393–396, doi:10.1029/GL012i006p00393.

Moore, C. B., K. B. Eack, G. D. Aulich, and W. Rison (2001), Energetic radiation associated with lightning stepped-leaders, *Geophys. Res. Lett.*, *28*, 2141–2144, doi:10.1029/2001GL013140.

Moreau, J.-P., J.-C. Alliot, and V. Mazur (1992), Aircraft lightning initiation and interception from in situ electric measurements and fast video observations, *J. Geophys. Res.*, *97*, 15,903–15,912.

Moss, G. D., V. P. Pasko, N. Liu, and G. Veronis (2006), Monte Carlo model for analysis of thermal runaway electrons in streamer tips in transient luminous events and streamer zones of lightning leaders, *J. Geophys. Res.*, *111*, A02307, doi:10.1029/2005JA011350.

Murooka, Y. A. (1992), A survey of lightning interaction with aircraft in Japan, *Res. Lett. Atmos. Electr.*, *12*, 101–106.

Nemiroff, R. J., J. T. Bonnell, and J. P. Norris (1997), Temporal and spectral characteristics of terrestrial gamma flashes, *J. Geophys. Res.*, *102*, 9659–9665, doi:10.1029/96JA03107.

Nguyen, C. V., A. P. J. van Deursen, and U. Ebert (2008), Multiple X-ray bursts from long discharges in air, *J. Phys. D*, *41*, 234012, doi:10.1088/0022-3727/41/23/234012.

Østgaard, N., T. Gjesteland, J. Stadsnes, P. H. Connell, and B. Carlson (2008), Production altitude and time delays of the terrestrial gamma flashes: Revisiting the Burst and Transient Source Experiment spectra, *J. Geophys. Res.*, *113*, A02307, doi:10.1029/2007JA012618.

Parks, G. K., B. H. Mauk, R. Spiger, and J. Chin (1981), X-ray enhancements detected during thunderstorm and lightning activities, *Geophys. Res. Lett.*, *8*, 1176–1179, doi:10.1029/GL008i011p01176.

Pelliccioni, M. (2000), Overview of fluence-to-effective dose and fluence to ambient dose equivalent conversion coefficients for high energy radiation calculated using FLUKA code, *Radiat. Protect. Dosimetry*, *88*, 279–297.

Plumer, J. A., N. O. Rasch, and M. S. Glynn (1985), Recent data from the airlines lightning strike reporting project, *J. Aircraft*, *22*, 429–433, doi:10.2514/3.45142.

Rahman, M., V. Cooray, N. A. Ahmad, J. Nyberg, V. A. Rakov, and S. Sharma (2008), X rays from 80-cm long sparks in air, *Geophys. Res. Lett.*, *35*, L06805, doi:10.1029/2007GL032678.

Rakov, V. A., and M. A. Uman (2003), *Lightning Physics and Effects*, Cambridge Univ. Press, New York.

Reazer, J. S., A. V. Serrano, L. C. Walko, and H. D. Burket (1987), Analysis of correlated electromagnetic fields and current pulses during airborne lightning attachments, *Electromagnetics*, *7*, 509–539, doi:10.1080/02726348708908196.

Saleh, Z., J. Dwyer, H. Rassoul, M. Bakhtiari, M. Uman, J. Howard, D. Concha, M. Stapleton, and D. Hill (2009), Properties of the X-ray emission from rocket-triggered lightning as measured by the Thunderstorm Energetic Radiation Array, *J. Geophys. Res.*, *114*, D17210, doi:10.1029/2008JD011618.

Shapiro, J. (2002), *Radiation Protection*, 4th ed., Harvard Univ. Press, Cambridge, Mass.

Shaw, G. E. (1967), Background cosmic count increases associated with thunderstorms, *J. Geophys. Res.*, *72*, 4623–4626, doi:10.1029/JZ072i018p04623.

Smith, D. M., L. I. Lopez, R. P. Lin, and C. P. Barrington-Leigh (2005), Terrestrial gamma-ray flashes observed up to 20 MeV, *Science*, *307*, 1085–1088, doi:10.1126/science.1107466.

Stanley, M. A., X.-M. Shao, D. M. Smith, L. I. Lopez, M. B. Pongratz, J. D. Harlin, M. Stock, and A. Regan (2006), A link between terrestrial gamma-ray flashes and intracloud lightning discharges, *Geophys. Res. Lett.*, *33*, L06803, doi:10.1029/2005GL025537.

Tsuchiya, H., et al. (2007), Detection of high-energy gamma rays from winter thunderstorms, *Phys. Rev. Lett.*, *99*, 165002, doi:10.1103/PhysRevLett.99.165002.

Uman, M. A., and V. A. Rakov (2003), The interaction of lightning with airborne vehicles, *Prog. Aerosp. Sci.*, *39*, 61–81, doi:10.1016/S0376-0421(02)00051-9.

Whitmire, D. P. (1979), Search for high-energy radiation near lightning strokes, *Lett. Nuovo Cimento*, *26*, 497–501, doi:10.1007/BF02750243.

Williams, E., et al. (2006), Lightning flashes conducive to the production and escape of gamma radiation to space, *J. Geophys. Res.*, *111*, D16209, doi:10.1029/2005JD006447.

Wilson, C. T. R. (1925), The acceleration of beta-particles in strong electric fields such as those of thunder-clouds, *Proc. Cambridge Philos. Soc.*, *22*, 534–538, doi:10.1017/S0305004100003236.

J. R. Dwyer, H. K. Rassoul, and Z. Saleh, Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA. (jdwyer@fit.edu)

B. Grefenstette, B. Hazelton, and D. M. Smith, Physics Department and Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064, USA.

M. A. Uman, Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611, USA.