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High-energy electron beams launched into space by thunderstorms

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[1] Using CGRO/BATSE data, a possible new source of high-energy electrons and positrons in the earth's inner magnetosphere is presented. These particles are generated within the upper atmosphere by Compton scattering and pair-production of gamma-rays originating from near the tropopause as Terrestrial Gamma-ray Flashes (TGFs). Once created, these energetic electrons and positrons follow the geomagnetic field into the inner magnetosphere where they can be detected in low-earth orbit, either near the TGF magnetic foot point or at the conjugate point several thousand kilometers away. Approximately 17% of CGRO/BATSE events previously identified as terrestrial gamma-ray flashes are, in fact, such electrons and positrons. With energies extending above 30 MeV, this previously unidentified population contains some of the most energetic particles accelerated in the near-earth environment.

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1. Introduction

[2] Terrestrial gamma-ray flashes (TGFs) are millisecond-long bursts of gamma-rays, detected by satellites in low Earth orbit, that come from the atmosphere with energies extending up to several tens of MeV. When they were serendipitously discovered in 1994 using data from the Burst and Transient Source Experiment (BATSE) on NASA's Compton Gamma-ray Observatory (CGRO) [*Fishman et al.*, 1994], they were found to be closely associated with thunderstorm and lightning activity [*Inan et al.*, 1996]. Indeed, maps of the world-wide TGF distributions made by BATSE and later by RHESSI show both a seasonal and geographic correlation with lightning, with lightning hot spots such as sub-Saharan Africa also having large concentrations of TGF detections [*Smith et al.*, 2005]. In addition, recent spectral measurements by the RHESSI spacecraft and accompanying modeling work have shown that the TGFs originate from altitudes <21 km in the atmosphere, within the range of thunderstorm tops and much too low for high-altitude phenomena such as sprites [*Dwyer and Smith*, 2005; *Carlson et al.*, 2007]. As a result, the picture has emerged that TGFs are the byproduct of massive numbers of runaway electrons being generated within or immediately above thunderstorms.

[3] Runaway electrons occur when the electric force acting on fast electrons exceeds the effective drag force experienced by those electrons as they move through air. In such cases, an avalanche of relativistic electrons can develop that produces large quantities of x-rays and gamma-radiation through bremsstrahlung interactions with air [*Gurevich et al.*, 1992; *Lehtinen et al.*, 1999; *Gurevich and Zybin*, 2001; *Dwyer*, 2003]. Even though gamma-rays suffer substantial attenuation in the atmosphere, large enough fluxes are produced at the source to allow detection at spacecraft altitudes. On the other hand, because the TGF source is so deep in the atmosphere, the runaway electrons are rapidly absorbed in air once they leave the avalanche region and so they will not be detected in space. In fact, after more than a decade of searching, no evidence of such runaway electron beams has ever been found. This result is problematic for models such as that recently proposed to explain the spoke structures in Saturn's rings. According to this model, beams of energetic runaway electrons, generated in association with thunderstorms on Saturn [*Dwyer et al.*, 2006], impact the rings producing the spoke structures that have been observed [*Jones et al.*, 2006].

2. Observations and Modeling

[4] Recently, during our reanalysis of CGRO/BATSE TGF data, one particular event stood out as not conforming to the established TGF pattern. Event number 2221 was detected in the middle of the Sahara desert during the winter, when all other TGFs were measured thousands of kilometers to the south. This event was also anomalously long, lasting about 30 milliseconds, with two widely separated peaks, rather than the typical 1 millisecond for most TGFs. BATSE event 2221 is reminiscent of another event measured by RHESSI in the winter of 2004 over the Sahara desert, also with two widely separated peaks [*Smith et al.*, 2006]. Because thunderstorms are not common in the Sahara, but the spacecraft was magnetically connected to a highly active thunderstorm region in south-central Africa with many TGFs, it is reasonable to speculate that event 2221 was not a TGF but rather energetic electrons propagating from the geomagnetic conjugate point. This then leads to the puzzle: how can energetic electrons escape into the magnetosphere and produce such intense events thousands of kilometers away when TGFs are produced deep in the atmosphere where no electrons can escape? In this letter, we shall present a new mechanism for thunderstorms to launch energetic electrons into the magnetosphere. Furthermore, we shall demonstrate that not only is BATSE event 2221 produced by high-energy electrons, but several other BATSE TGFs have likely been misidentified and are also electron events rather than gamma-ray flashes. Thus, there exists a population of high-energy electrons in the earth's inner magnetosphere that was previously unrecog-

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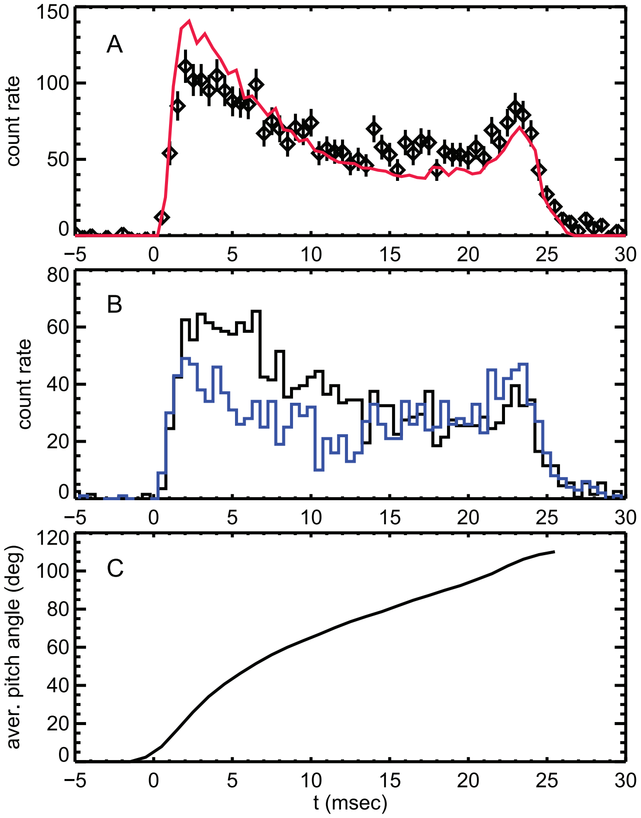

Figure 1. (a) Total count rate for BATSE TGF 2221 along with the model results (red curve). The second peak is due to magnetic mirroring of the electrons by the geomagnetic field near the closest foot point. (b) Count rate for BATSE TGF 2221. The black data are the sum of the 4 brightest LADs and the blue data are the sum of the 4 dimmest LADs. As can be seen the event becomes isotropic over time, indicating that BATSE is detecting electrons rather than gamma-rays. (c) Average electron pitch angle at the CGRO/BATSE location for an electron beam produced at the far geomagnetic foot point.

nized. This paper presents the first direct evidence that such electron beams associated with thunderstorms do occur in the magnetosphere and has direct implications for energetic particle population in other planetary magnetospheres such as Jupiter and Saturn.

[5] The proposed mechanism is as follows. As the gamma-rays that compose a TGF propagate up through the atmosphere, they interact with air atoms, predominantly via Compton scattering and pair-production. Most of the secondary, Compton electrons and pair-produced electrons and positrons are quickly absorbed in the atmosphere. However, above about 40 km, a significant fraction of these secondary electrons and positrons can escape the atmosphere and propagate into the inner magnetosphere along the local geomagnetic field lines. We note that this mechanism is different from previously proposed mechanisms for injecting energetic electrons in the magnetosphere [*Lehtinen et al.*, 2000, 2001], since the production mechanism of the electrons is different and it does not require a high-altitude source of runaway electrons [*Papadopoulos et al.*, 1996; *Papadopoulos and Valdivia*, 1997]. In addition, unlike earlier models, this mechanism is an inevitable result of a gamma-ray beam exiting an atmosphere, and so it must occur whenever terrestrial or planetary gamma-ray flashes occur.

[6] Detailed Monte Carlo simulations were performed to calculate the time-intensities of electron beam events as would be measured near the conjugate points of the geomagnetic fields. This Monte Carlo has been reported on extensively elsewhere [*Dwyer and Smith*, 2005; *Dwyer*, 2007] and so will only be summarized here. The simulation includes, in an accurate form, all the relevant physics for describing the interactions of photons and energetic electrons with air [*Dwyer*, 2003]. The energetic electrons and positrons are propagated using a Runge-Kutte method to solve the relativistic equations of motion of the particles moving in external electric and magnetic fields. The particle interactions include energy losses through ionization and atomic excitation, Møller scattering for secondary electron production and elastic scattering. Bremsstrahlung production of x-rays and gamma-rays and the photon propagation is fully modeled, including photoelectric absorption, coherent and Compton scattering and pair production. Furthermore, bremsstrahlung production from all secondary electrons and positrons and positron annihilation gamma-rays are included.

[7] For these simulations, the source altitude, where the runaway electrons are generated and where the gamma-rays are produced via bremsstrahlung interactions, is located at 21 km and the runaway electrons are assumed to be beamed vertically upward. This configuration produces a gamma-ray spectrum consistent with the RHESSI TGF spectrum. As expected, the simulation shows that the primary runaway electrons do not exit the atmosphere due to their rapid absorption after leaving the runaway avalanche region.

[8] The secondary electrons in the Monte Carlo simulation exiting the top of the atmosphere were then propagated along the geomagnetic field line. During the propagation, the first adiabatic invariant was conserved to include pitch angle focusing and magnetic mirroring effects. Also included were backscattering and absorption in the atmosphere at the conjugate point. Particle drifts were found to be very small and so could be safely ignored. Wave-particle interactions, which tend to isotropize the electrons, may occur in some cases [*Moghaddam-Taaheri et al.*, 1985] as the electrons propagate within the magnetosphere, but these interactions were not included in this study. The geomagnetic field were calculated for the specific spacecraft location and date of each event according to The International Association of Geomagnetism and Aeronomy (IAGA) 10th Generation International Geomagnetic Reference Field (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html).

[9] Results of the simulation are shown in Figure 1 along with the CGRO/BATSE data for event 2221. The top panel shows the fit of the model to the BATSE counts data. The second peak is due to the magnetically mirrored electrons. Interestingly this reflected component can be more sharply peaked in time than the original distribution that passed by the spacecraft. There are two causes of this: first, electrons with small pitch angles will strike the atmosphere and most will be absorbed. Second, the mirroring electrons with the smallest pitch angles pass the spacecraft first, but they also

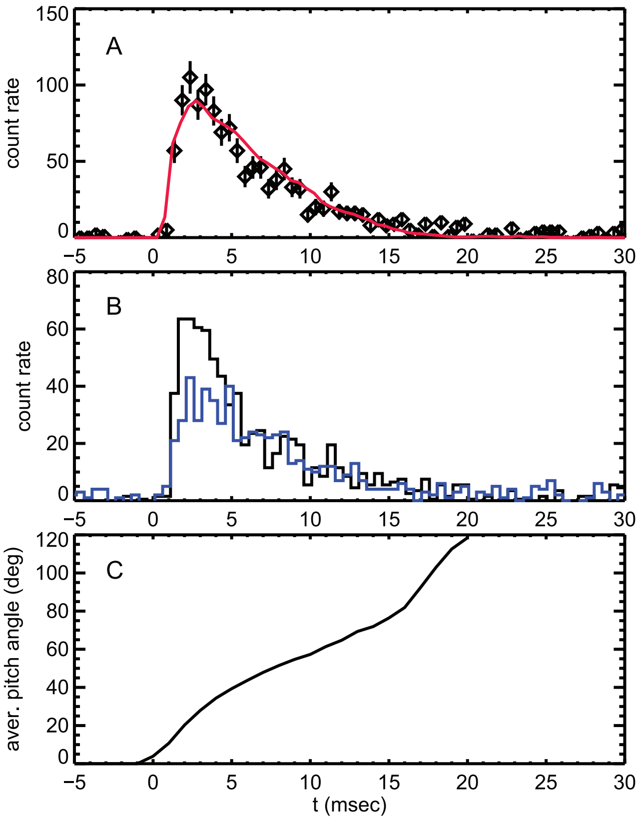

Figure 2. (a) Total count rate for BATSE TGF 1470 along with the model results (red curve). Unlike 2221 shown in Figure 1, the geomagnetic field does not produce magnetic mirroring at the closest foot point, so no second peak occurs. (b) Count rate for BATSE TGF 1470. The black data are the sum of the 4 brightest LADs and the blue data are the sum of the 4 dimmest LADs. As can be seen the event becomes isotropic over time, indicating that BATSE is detecting electrons rather than gamma-rays. (c) Average electron pitch angle at the CGRO/BATSE location for an electron beam produced at the far geomagnetic foot point.

propagate the farthest past the spacecraft before mirroring and returning to the spacecraft position a second time. On the other hand, the electrons with the largest pitch angles initially arrive later but mirror almost immediately. This causes a kind of focusing in time. Simulations show that the number of energetic electrons (>100 keV) striking the spacecraft is about 2 times greater than the number of gamma-rays from a typical TGF. We emphasize that the excellent agreement of the model with the time profile is obtained with no free parameters except a small adjustment in the overall normalization. It is the necessary result, after deterministic stages of gamma and secondary electron production and propagation, of the initial, instantaneous injection of primary relativistic electrons near the tropopause.

[10] When analyzing the arrival directions of event 2221, using the eight BATSE Large Area Detectors (LADs) located on the corners of CGRO, it was found that this event had a very distinctive time development of the arrival directions, with the event starting off anisotropic and then becoming almost completely isotropic during the event (Figure 1b). Such behavior cannot be explained by gamma-rays but can easily be accounted for by the evolution of the pitch angle distribution of the electrons, with the small pitch angle electrons arriving first, followed several milliseconds later by the larger pitch angle electrons. These larger pitch angle electrons are recorded as an approximately isotropic distribution by the 8 LADs. Indeed, the arrival direction towards the end of event 2221 is slightly reversed from that of the start of the event, consistent with the presence of a mirrored component. The bottom panel shows the average pitch angle predicted by the model at the spacecraft location for a TGF located near the far magnetic foot point. As can be seen, the average pitch angle changes from field-aligned to a distribution with large pitch angles.

[11] A reanalysis of the 36 TGFs available via the public CGRO Legacy archive [ftp://legacy.gsfc.nasa.gov/compton/data/batse/trigger] has identified 5 additional events that have time development of the arrival directions similar to event 2221 and so are very likely to be electron beam events. These electron beam events have BATSE IDs: 1470, 2221, 2248, 2457, 7229, and 7208, with 1470 and 2221 being the conjugate events. The second conjugate electron beam event (BATSE TGF 1470) is shown in Figure 2 along with the model results. Because this event was located south east of Japan, the geomagnetic field was weaker at the foot point near the spacecraft and so no magnetic mirroring is expected to occur and there should not be a second peak as in TGF 2221. As can be seen, the model is in excellent agreement with the observations.

[12] In order to account for the RHESSI TGF observations [*Dwyer and Smith*, 2005], the total energy of the runaway electrons produced in the source region is about $10^4 – 10^5$ J, depending upon the source altitude. This energy is many orders of magnitude smaller than the energy available from the electric field inside thunderstorms. The number of gamma-rays produced at the source region is about 1.5 times the number of runaway electrons, and the total energy of the emitted gamma-rays is about 20% that of the runaway electrons. Simulations show that for every 100 gamma-rays that escape to space above 100 keV, about 1 escaping energetic electron is produced, and these energetic electrons have about 1% the total energy of the gamma-rays. About 1.6% of this population is positrons. Figure 3 shows the differential energy spectra of the gamma-rays and the electrons that exit the atmosphere. As can be seen, simulations show that the electron spectrum extends to very high energy, in excess of 30 MeV, making these electrons among the most energetic of those produced in the near earth environment.

[13] While the gamma-rays spread out as they propagate to spacecraft altitudes, with intensities falling off as $1/r^2$, the electrons remain confined to the field lines that they were formed on and maintain approximately the same intensity as they propagate to the spacecraft. Figure 4 shows the number/unit area of the gamma-rays and the electrons at 500 km. Note that the peak of the electron distribution exceeds that of the gamma-rays by about a factor of two. The radius of the electron distribution shown in Figure 4 is about 1/10 that of the gamma-ray distribution. As a result, the probability of a spacecraft encountering an electron

beam is about 1% that of the gamma-rays, but this number should be multiplied by two when considering that the electrons can also be observed near the conjugate point of the magnetic field after travel through the inner magnetosphere. In addition, these electrons should also be observable with high-altitude balloon experiments at both the TGF source region and the geomagnetic conjugate point.

[14] A recent study of BATSE TGF data showed that for most TGFs, BATSE experienced significant dead-time due to the high count rates, making it less sensitive to bright but short duration TGFs. Because the electron beam events have longer durations due to the propagation of the electrons and because they are more intense on average than the gamma-ray events, they may preferentially trigger the BATSE instrument. As a result, instead of the electron beam events making up ~1% of the BATSE data set as would occur if all electron and gamma-ray events could be measured, based purely upon the beam geometries, they make up closer to 17% of the 36 TGF available for study.

3. Summary

[15] We have found that a substantial fraction of Terrestrial Gamma-ray Flash (TGF) events observed by the CGRO/BATSE instrument are, in fact, not gamma-rays at all but instead are a new class of events composed of high-energy electrons exiting the atmosphere and propagating back and forth along the geomagnetic field in the inner magnetosphere. We have presented a model that can fully account for these electron beams. In this model, electrons and positrons are knocked out of the atmosphere by Compton scattering and pair-production by the gamma-rays associated with TGFs. Because all TGFs are expected to make such electron/positron beams and because recent RHESSI observations have shown that due to BATSE triggering and dead-time issues the occurrence rate of TGFs is an order of magnitude greater than previously inferred, these high-energy electron/positron beams must also be a fairly common occurrence in the inner magnetosphere. Finally, lightning is also known to occur in the Jovian planets and may result in similar gamma-ray flashes originating from those planet's atmospheres. As a result, electron and positron populations similar to those reported here may occur in other planetary magnetospheres as well.

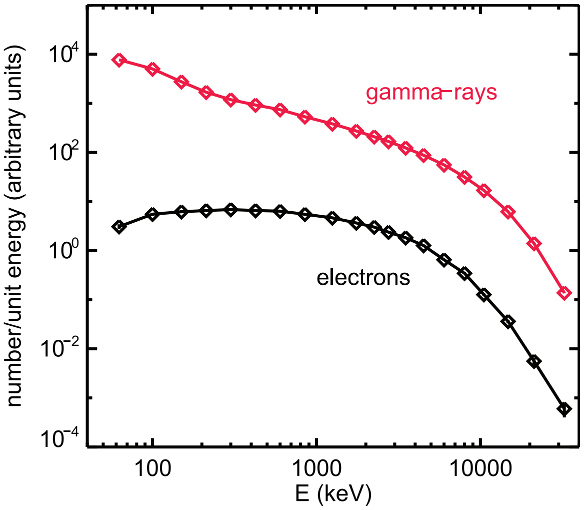

Figure 3. Differential energy spectra of electrons (black) and gamma-rays (red) exiting to space.

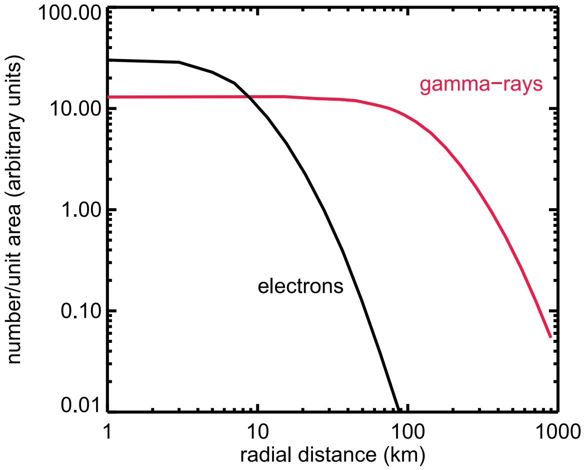

Figure 4. Number per unit area of electrons (black) and gamma-rays (red) versus radial distance at 500 km altitude. For the gamma-rays, the radius is measured from the beam axis, located vertically above the TGF. For the electrons the radius is measured from the center of the electron beam, which exits the atmosphere along the geomagnetic field line at 40 degrees with respect to vertical in this case.

[16] **Acknowledgments.** We wish to thank Hamid Rassoul for his assistance with the geomagnetic model. This work was supported by the NSF grant ATM 0607885.

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