Observations of Terrestrial Gamma-Ray Flash Electrons

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Abstract. Terrestrial gamma-ray flash (TGF) emissions are predicted to be accompanied by energetic electron emissions. These electrons have been suggested to explain several anomalous TGF observations by the RHESSI and BATSE spacecraft. These electrons additionally provide a new window for study of TGFs as they carry additional information about the source through their pitch angle / arrival time distributions and confinement by the geomagnetic field. This information could prove very useful for analysis of TGF source mechanisms.

We present results of simulations of electron and photon emissions and describe the implications of these results for inferences about the TGF source. We also present the results of a search of data from the SAMPEX satellite for these electrons and discuss in particular two events with multiple strong pulses of electrons.

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INTRODUCTION

Terrestrial gamma-ray flashes (TGFs) are energetic bursts of photons first observed by the Burst And Transient Source Experiment (BATSE) on board the Compton Gamma-Ray Observatory (CGRO) [1]. These pulses of photons are typically ~ 1 ms long, have a fluence that can approach 1 cm^{-2}, and an energy spectrum slightly harder than $dN/dE \propto 1/E$ ranging from less than 10 keV to above 20 MeV [2]. When good lightning data are available, TGFs are typically observed in coincidence with a lightning discharge less than 300 km from the subsatellite point and within 1 ms of the expected source time when time delays are accounted for [3, 4, 5, 6].

TGFs are thought to be the result of a runaway relativistic electron avalanche (RREA) process whereby relativistic electrons undergo avalanche multiplication when driven by electric fields. The lower dynamic friction on relativistic electrons compared to low-energy electrons allows RREA to take place at electric fields an order of magnitude lower than the fields necessary to drive avalanche multiplication of low-energy electrons (conventional breakdown) [7, 8]. These much lower electric field requirements suggest RREA as important for many aspects of atmospheric electricity including sprites [9, 10], blue jets [11], and lightning initiation [12, 13].

Electrons undergoing RREA in air produce a characteristic spectrum of bremsstrahlung photons. Simulations of these photons as they propagate upwards through the atmosphere and are observed by satellites allows comparison between the satellite observations and the predictions from models of the TGF source. Subject to the assumption that all TGFs are emitted at the same altitude, TGF source models reproduce the average observed spectrum if the photons originate at altitudes ranging from 15 to 20 km [14, 15], though when treated individually some TGFs seem to originate from much higher altitudes [16].

Occasionally, however, a TGF is observed that does not fit this pattern. These anomalous TGFs are much longer and can be quite intense, perhaps lasting up to 10 ms long. It has been suggested that these anomalous "TGFs" are not really photon pulses, but are in fact electrons emitted in conjunction with the photons: RREA electrons deep in the atmosphere emit bremsstrahlung, which emits electrons and positrons by Compton scattering and pair production, some of which can escape the atmosphere[17]. Though deadtime issues have been raised [18], some anomalous TGFs observed by the BATSE instrument are very well fit by this model [see Monte Carlo results in 17], lending credence to the straightforward notion that if energetic photons are emitted, so should energetic electrons as a simple consequence of Compton scattering and pair production. We suggest these energetic electron bursts be called Terrestrial Electron Flashes (TEFs).

Unfortunately, most existing TGF data comes from the RHESSI and BATSE satellites which are not designed to detect electrons. In the case of the anomalous TGF observations, the satellites are likely detecting bremsstrahlung produced in the spacecraft by the energetic electrons. If this indirect detection method is successful, direct detection of the electrons should also be possible. Data from a suitable electron detector are already available: the Solar Anomalous Magnetospheric Particle Explorer (SAMPEX), launched in 1992 and still in operation, has been measuring electron count rates at 20 ms time resolution for many years [19]. We herein describe a search through SAMPEX data for the signature of TGF electrons. First we describe a Monte Carlo model of electron emission and escape to determine the signature expected. Second, we describe the search through the satellite data and give the results of the search. Finally, we discuss the implications of our search results for TGF physics and describe inferences that may be possible as a result of further study.

TERRESTRIAL ELECTRON FLASH (TEF) SIMULATIONS

The signature of electron emissions can be modeled on the basis of existing models of TGF emission. These models involve RREA, which produces a characteristic spectrum of photons as mentioned above. We therefore simulate electron emissions by starting an initial population of electrons or photons at an initial altitude of 20 km in a standard atmosphere [see 20] with a uniform 0.4 gauss magnetic field with dip angle 45°. We run simulations with the GEANT4 software package [21], a standard high-energy particle physics simulation package that includes all relevant physics including bremsstrahlung, ionization, multiple scattering, Compton scattering, pair production, and photoelectric absorption. Simulations of electrons started deep in the atmosphere indicate that very few initial electrons directly escape as they are heavily attenuated, so we focus instead on simulations where an initial population of photons is started at 20 km initial altitude with an energy spectrum given by bremsstrahlung from the characteristic RREA electron energy spectrum [taken from 10]. These photons and the electrons they produce are then tracked until the particles are either absorbed or reach satellite altitude, here chosen to be 600 km.

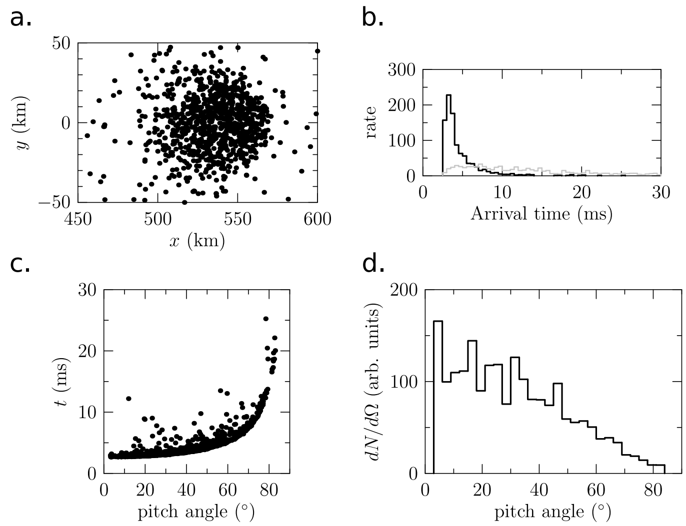

FIGURE 1. Results of simulations of properties of electrons emitted along with photons in a TGF. Properties shown when electrons first reach satellite altitude. a. distribution in plane at satellite altitude. b. arrival time distribution at satellite altitude (black), arrival time distribution spread out by a factor of 10 (grey). c. arrival time as a function of pitch angle. d. pitch angle distribution.

The resulting properties of the escaping electrons are shown in Figure 1. Figure 1a shows the locations where the particles first reach satellite altitude: the electrons are confined by the magnetic field to a beam $\sim$ 50 km wide. The black line in Figure 1b shows a histogram of the arrival time (the time when the electrons first reach satellite altitude): the electrons arrive in a pulse a few milliseconds wide. Figure 1c shows the arrival time versus the pitch angle of the particles with respect to the geomagnetic field, demonstrating that the pitch angle closely determines the arrival time. As the arrival time is determined by the pitch angle, we can crudely approximate the arrival time distribution for electrons that have propagated further along the field line simply by multiplying their arrival times by a constant. If the electrons are observed not at the first time they reach satellite altitude, but after they have traveled to the conjugate hemisphere and again cross satellite altitude, they will have propagated a factor of $\sim$ 10 further along the field line, resulting in an arrival time distribution shown in grey in Figure 1b. Figure 1d shows the pitch angle distribution itself, showing that the electrons are directed along the magnetic field as expected. The relative number of photons and electrons emitted in such a TGF indicates that roughly 100 photons escape for every electron that escapes, while the electrons cross satellite altitude in an area roughly 100 times smaller than the area crossed by the photons, leading to roughly comparable fluence for electron observations and photon observations. These results are in good agreement with similar analyses in [17].

These simulation results lead us to expect that the signature of electrons emitted in conjunction with TGF photons will be a brief 2-10 ms pulse of ~ 1 electrons per cm^{-2} spread over a relatively narrow region 50 km wide, directed more or less along the magnetic field. We will therefore tailor our search through SAMPEX data to find such pulses.

SATELLITE DATA SEARCH

SAMPEX Data Products

The Solar Anomalous Magnetospheric Particle Explorer (SAMPEX) satellite is a NASA small explorer satellite launched in 1992 and still in operation [19]. The main instrument on board SAMPEX useful for our purposes is the Heavy Ion Large Telescope (HILT), a drift chamber and proportional counter system combined with an array of solid state detectors (SSDs) and scintillators designed to measure nucleons but with a substantial sensitivity to electrons with energies in excess of 1 MeV [22]. HILT has negligible sensitivity to energetic photons. When operating in high time resolution mode, the HILT records electron count rates in the SSDs with 20 ms time resolution and an effective geometric factor of 60 cm^2sr. The HILT was switched to this mode on August 7, 1996 and continues to record data. Here we focus on the approximately 8 years of data collected between August 7, 1996 and June 30, 2004. The data set therefore represents a number of electrons incident on the SSDs every 20 ms for 8 years. As BATSE and RHESSI have seen likely electron beam events in similar size data sets, we expect this to be a sufficient quantity of data though the complexity of event identification, triggering, and search algorithm efficiency make it difficult to directly compare event rates between spacecraft.

This very rich data set contains much interesting physics, but our signature as described above is a brief pulse of electrons with a total fluence of $\sim 1\ \mathrm{cm}^{-2}$ lasting up to 10 ms. We therefore expect a maximum of order 50 counts. As 10 ms is shorter than the 20 ms time resolution, we expect these counts to be spread over only one or two bins. This is the target for our search. As 50 counts is a small fraction of the maximum count rate observed by HILT, we must reject regions where the satellite experiences high background count rates, i.e. high latitude regions and the South Atlantic Anomaly, where HILT records primarily radiation belt electrons and any TEF signal will be overwhelmed. The remaining data set consists of low, slowly-varying background, punctuated by the occasional large statistical fluctuation or TEF.

Search Method

We search this data set simply by scanning one bin at a time with a 3-bin wide region of interest (ROI). The background count rate is estimated by taking an average of 40 bins before and 40 bins after the region of interest. The number of counts in the region of interest is compared to the number of counts expected given the background estimate, and if the probability of observation of as many or more than the observed number of ROI counts is less than 1 in 10^9 as given by Poisson statistics, the event is flagged as interesting.

These "interesting" events are then treated more rigorously. The background count rate as estimated by averaging 40 bins before and after the region of interest is subject to statistical fluctuations, and these fluctuations can have a major effect on the calculated probability of observation of such an event. We therefore compensate for this by

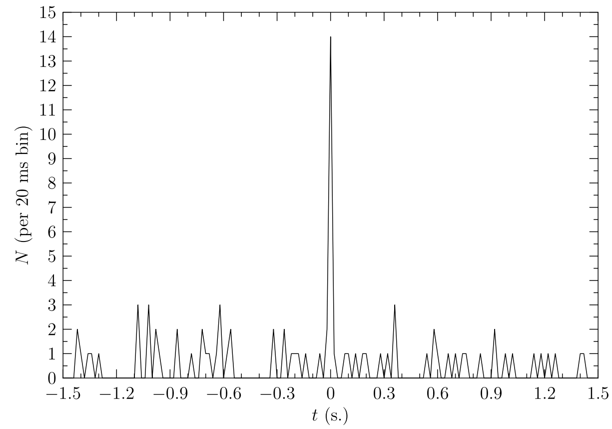

FIGURE 2. A typical search result. Event occurred at November 28, 2002, 4:34:16.12 UT. Satellite latitude/longitude −2.65°N/166.95°E, *L*-shell 1.11.

calculating $p(n \geq n_{\text{obs}}|b_{\text{obs}})$, the probability of observing $n \geq n_{\text{obs}}$ counts given that we observe b_{obs} background counts, calculated as an average over the unknown true background count rate. This allows the true background count rate to be higher than the observed background count rate by allowing for statistical fluctuations in the observed background count rate. This is especially relevant for cases where only a few counts are observed in the ROI, but the observed background count rate is very low (even zero). This averaging procedure substantially raises the probability of observation and leads to a much more reliable calculation of significance of the event. At this pass, the new probability is again required to be less than 1 in 10^9. Count rate data recorded every 20 ms for 8 years yields $\sim$ 13 billion independent data points, so threshold should pass only 13 false positives. Roughly 50 events are found, a very large excess when only 13 are expected.

SEARCH RESULTS

A sample search result is shown in Figure 2. 10 to 15 counts are spread over 1 or 2 bins in the ROI, with a low surrounding background count rate. These events make up the bulk of the search results. Statistical fluctuations should account for a portion of these events. Cosmic rays impacting the satellite also may contribute, but the extremely short timescale of a cosmic ray interaction would likely outrun the electronics and lead to only a few recorded counts though further analysis is required.

The geographic locations of the satellite when the events were observed are shown in Figure 3. The expected geographic distribution is complicated by the fact that large regions where lightning is very common are located at sufficiently low *L*-shells that any emitted electrons propagating along the geomagnetic field would not reach SAMPEX orbit altitude (550-675 km) and thus could not be observed. A full analysis of *L*-shell, total lightning frequency, intense lightning frequency, and satellite coverage would be required for meaningful comparison between expected and observed event distributions.

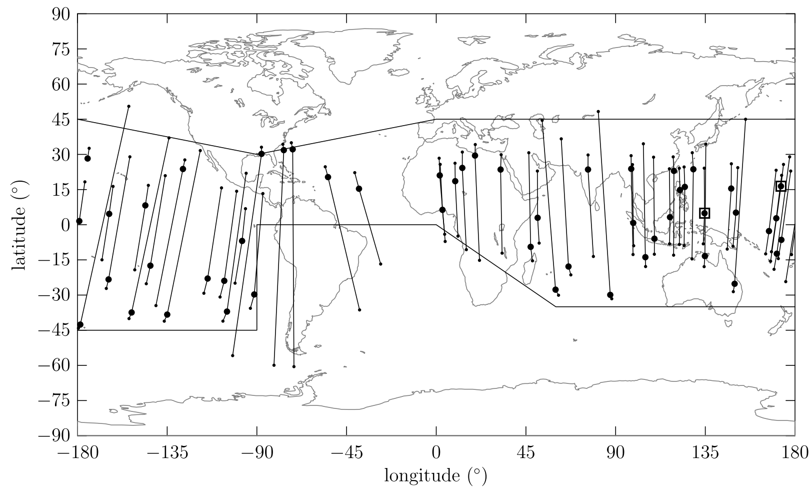

FIGURE 3. Geographic location of the satellite when events were observed. Large dots represent the satellite location, with the satellite's north and south geomagnetic footprint indicated by small dots connected by lines to the associated satellite location. The lines running across the map isolate the region below the radiation belts where the search was executed.

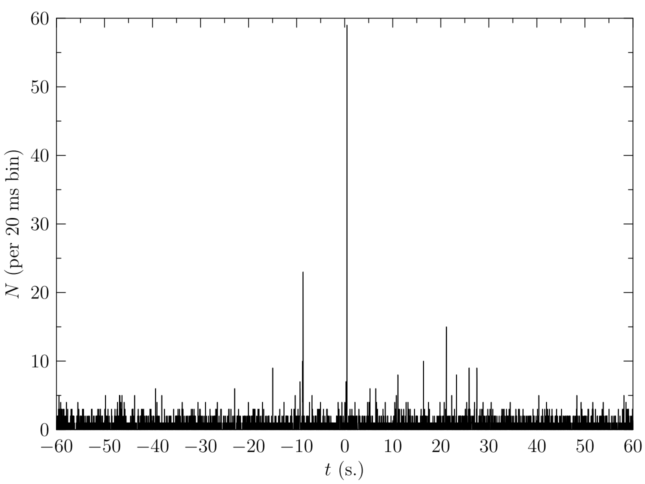

FIGURE 4. One of two cases where many flashes occurred in less than a minute. Main peak occurred at May 8, 1998, 8:55:01.5 UT. Satellite latitude/longitude −5.47°N/106.52°E, *L*-shell 1.17.

Such analysis is pending.

The most interesting search results are represented by the event shown in Figure 4, in which many very significant peaks are recorded in less than a minute. There are two such cases in our 8 year data set. Such cases cannot be explained as statistical fluctuations as they are far too significant, nor as instrumental anomalies such as cosmic ray impacts as there is a clear cluster of peaks. The geographic locations of these two events are marked with boxes in Figure 3.

DISCUSSION

These events provide clear evidence that electron flashes occur and are observable by the SAMPEX spacecraft. This affords us an opportunity to examine the physics of such electron flashes thanks to several properties of the events. First, the events are short, allowing for a search for close time coincidences with other data sources. This will allow correlation with lightning observations. If the hypothesis that these electron flashes are emitted in conjunction with TGFs, we would expect to find signals from associated lightning. Second, as electrons are confined by the geomagnetic field, these events afford us an opportunity to trace back to the source of the electrons. The geomagnetic footprints of the satellite location of a lightning-associated event would be located in the source storm, allowing for close meteorological connections. Third, the frequency of observations of electron flashes allows us to constrain the effective size of an electron flash with respect to the true frequency of electron flashes. This analysis can be connected with models of TGF emission and the frequency of TGF observation to constrain the effective size of a TGF relative to the effective size of an electron flash. Finally, the observation of the electrons may directly constrain the source model, similar to the analysis of photons observed by RHESSI and BATSE [as in 15, 14]. Pursuit of these analyses is ongoing.

SUMMARY

We have presented an analysis of the idea that TGFs may be accompanied by electron emissions in a terrestrial electron flash (TEF). Analysis of the expected signature of a TEF leads to the possibility of observation by the SAMPEX satellite. A search through SAMPEX data for the signature of these events finds many more candidates than would be expected on the basis of simple statistical fluctuations. Two cases are observed where there are many flashes within less than a minute. These events are clear evidence for new physics as no similar events have been previously observed.

The search results indicate electron flashes occur and are observable, though we have yet not completed an analysis of possible correlation between our electron flashes and TGFs, lightning, or storms. Such searches will be useful in the future for analysis of electron flash physics and TGF physics, and may have implications for the physics of storms and of the radiation environment in near-Earth space.

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