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THE EXISTENCE OF TERRESTRIAL GAMMA-RAY FLASHES THAT PARALYZE RHESSI

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Abstract

The Existence of Terrestrial Gamma-Ray Flashes

that Paralyze RHESSI

by

Alexander Infanger

We argue for the existence of Terrestrial Gamma-ray Flashes (TGFs) that paralyze the Reuven-Ramaty High Energy Solar Spectroscopic Imager (RHESSI). We present a catalog of candidate RHESSI-paralyzing TGFs (RPTs), and show that the candidates originate from thunderclouds as opposed to cosmic sources. We do this by (1) indicating properties in the RPTs' time series that are associated to TGF characteristics and (2) demonstrating a correlation between the candidate RPTs with World Wide Lightning Location Network (WWLLN) radio sferics and the Grefenstette catalog of standard TGFs (Grefenstette et al. 2009). For (1), we show that the hitherto accepted TGF production mechanism known as the Relativistic Runaway Electron Avalanche (RREA) and the Compton scattering of gamma-rays in the atmosphere both produce observable characteristics in the candidates' time series. For (2), we produce empirical distributions for three quality factors using 1000 randomly generated catalogs. The quality factors are (1) WWLLN storm match rate, (2) WWLLN flash match rate, and (3) geographical/seasonal correlation with the Grefenstette catalog of TGFs. We show that the candidate RPTs are not a random set of dates with greater than 98% confidence in all cases, where we assume that the errors in our sample distributions are negligible.

Contents

Acknowledgements

I especially thank Professor David Smith for guiding this thesis work. Our weekly meetings were shots of adrenaline to the neck, which kept me focused when results were not in sight. I also thank my father, Professor Gerd Infanger, for being a loving soundingboard and informal collaborator; indeed, his technical insights landed him on a TGF paper before even me. I thank professor Peter Glynn for the conversations we had on modeling RHESSI background in the summer of 2015. While new developments on the research front stopped me from persuing the model we were floating at the time, Peter's ideas kindled new ideas and motivation that helped in the fruition of this thesis.

Thanks to Professor Adriane Steinacker for giving me a taste for scientific prose and for being my friend, and to professor David Belanger for coordinating my thesis in the middle of August. Thanks to Nicolette Nodine for being the meanest and sweetest copy editor in Santa Cruz, and to my mom and step-dad, Massy Safai and Richard Foley, for their love and support. For Massy: Albert Camus!

I find the work hard, thank God, & almost pleasant.

– J.R. Oppenheimer

1 Introduction

In order to introduce Atmospheric Electricity (AE) coherently, it is useful to categorize it into four subclasses: (1) lightning, (2) Transient Luminous Events (TLEs), (3) the Global Electric Circuit (GEC), and (4) Terrestrial Gamma-ray Flashes (TGFs). We introduce the four categories in the following paragraphs, giving special attention to TGFs because we hope to show the existence of a new subclass of TGFs in this thesis.

Probably the most familiar form of AE to the reader is lightning. It is curious that lightning occurs at all, considering that electric fields in thunderclouds are consistently measured to be an order of magnitude less than the dielectric strength of air (DSA) [1–4]. Many theories of lightning initiation compete to resolve this paradox (see the review by D. Petersen et al. [5]), but there is a general consensus that water droplets and ice crystals, which are conductive compared to air, locally enhance electric fields in thunderclouds; if the potential difference exceeds the DSA in a small region of charge, then the air ionizes and produces small currents, known as streamers. Through a funneling process the streamers intensify and conglomerate into a hot conducting channel referred to as the leader. The leader propagates itself out of the region by thermally ionizing the air around it and so providing charge to its tip, which – like the conducting droplets – produces streamers that intensify and propel the leader forward [6–8].

Note that we use the word "current" broadly here. The initial charge in motion can be negative or positive ions [9, 10]. During thermal breakdown, the positive (negative) leader moves quasi-randomly, generally following (opposing) the electric field, until it reaches a charge center. When this happens, the leader has burned a conductive channel between two charge centers, and hence current flows [10]. With respect to charge signs, we adopt the standard meteorological nomenclature, in which the +(-) that prefixes a flash category signifies that the lightning moves positive (negative) charge down, or negative (positive) charge up.

Theory aside, we observe that lightning either takes the form of cloud-to-ground (CG) or intra-cloud (IC) flashes. H.J. Christian et al. [11] used measurements from the space-based Optical Transient Detector (OTD) to estimate that the Earth houses 44 ± 5 IC and CG discharges per second, with IC flashes comprising 3/4 of the total frequency [10]. They also showed that the geographical distribution of lightning is not uniform. We present the global distribution of lightning as measured by the OTD in Fig. 1.1, which shows maxima in the tropics, where atmospheric convection inspires more violent weather [12].

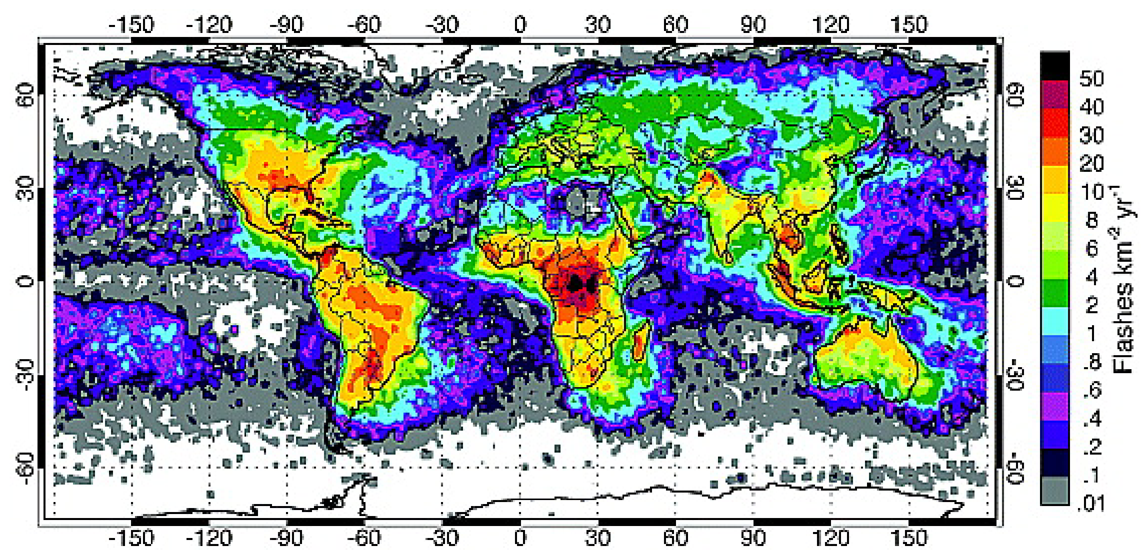


Figure 1.1: The global distribution of lightning, integrated annually and averaged over five years of OTD data (1995 to 2000). From Christian et al. [11].

At this point the reader may wonder why thunderclouds develop in the first place. Cloud electrification is still under investigation and beyond the scope of this work. It suffices to say that certain pairs of hydrometeors are favored to exchange charge in one direction upon collision; then, via precipitation and/or convection, the different hydrometeors drift to separate regions of the clouds [13–15]. An accepted model that was first proposed by G. Simpson, G. Robinson, and F.J. Scrase posits that a thundercloud develops upper positive, main negative, and lower positive regions: the upper positive region corresponds to temperatures $< -10°$ C, the main negative region corresponds to temperatures between -10° C and 0° C, and the lower positive region corresponds to temperatures $> 0°$ C [16, 17]. We show such a cloud configuration in Fig. 1.2.

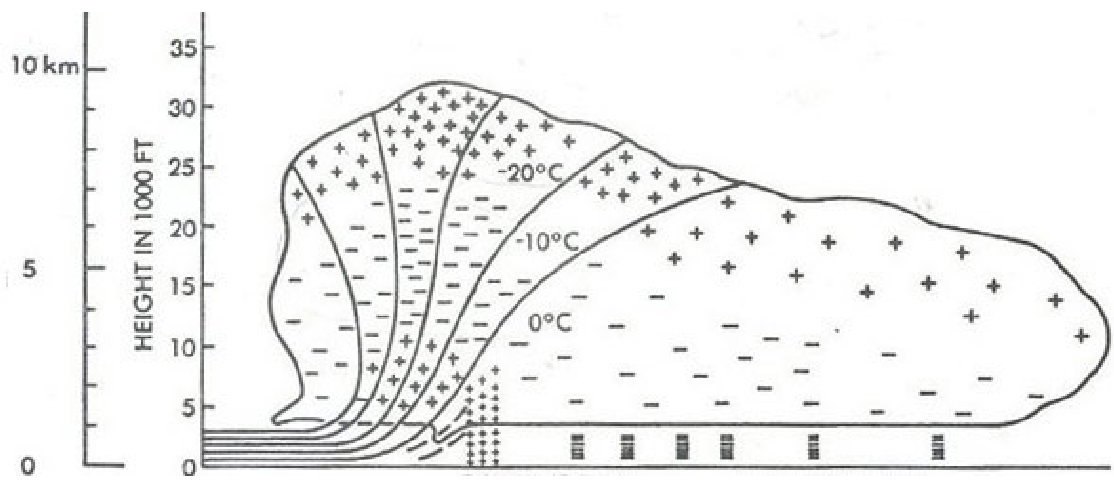


Figure 1.2: A graphical depiction of a thundercloud. Adapted from Simpson and Scrase [16].

More colorful bursts of electricity exist above thunderstorms; these include sprites, jets, and Emissions of Light and Very low frequency perturbations due to Electromagnetic pulse sources (referred to as ELVEs or elves), which all together make up the category of TLEs. We present an artist's rendition of the various TLEs in Fig. 1.3.

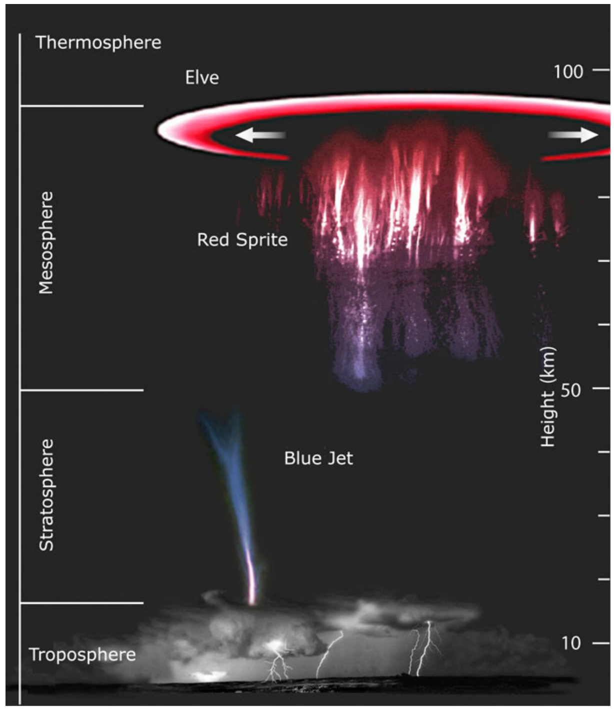


Figure 1.3: A drawing of the various TLEs which shows their respective heights in the atmosphere. Adapted from Neubert [18].

Sprites are clusters of red discharges that occur above thunderstorms in the mesosphere; they last between 5 and 300 ms and span 20-50 km in radius [19–21]. R.C. Franz et al. [22] presented the world's first sprite measurement when they published a picture of a sprite that flared over the northwestern side of Lake Superior in the summer of 1990. Since then, higher resolution photographs have been published by D.D. Sentman et al. in 1995 [19], W.A. Lyons in 1996 [23], and others [24–27]. See, for examples, the photographs in Fig. 1.4 and Fig. 1.5. Franz et al. describe sprite structure as having "a fan shaped upper plume with very fine features [with] dendritic (upward forked) and vertically striated forms adjacent to these plumes and bright points of luminosity around the plume-shaped regions." [22] Note that while Franz et al. reported a sprite with an upper plume, sprites with lower plumes or both plumes have also been observed [21, 28, 29].

D.J. Boccippio et al. [30] empirically showed that sprites tend to occur after +CG flashes. A few theories of sprite initiation were developed in light of this result [31, 32], but the most accepted mechanism is from V.P. Pasko et al. [33]. Pasko et al. pointed out that (1) the DSA falls exponentially with altitude [34], and (2) the upper positive region of any thundercloud induces negative space charge in the conducting lower ionosphere. If a +CG flash removes a significant amount of positive charge form the upper positive region, then the fields in the upper ionosphere exceed the DSA, and streamers discharge the fields. We show a time-line of this effect in Fig. 1.6.

Figure 1.4: A photograph taken from the International Space Station which shows a coincident sprite/lightning event (look to the extreme right). From NASA [26].

Figure 1.5: A photograph taken from a National Center for Atmospheric Research airplane which shows a narrow sprite against a setting sun. From Ahrns [27].

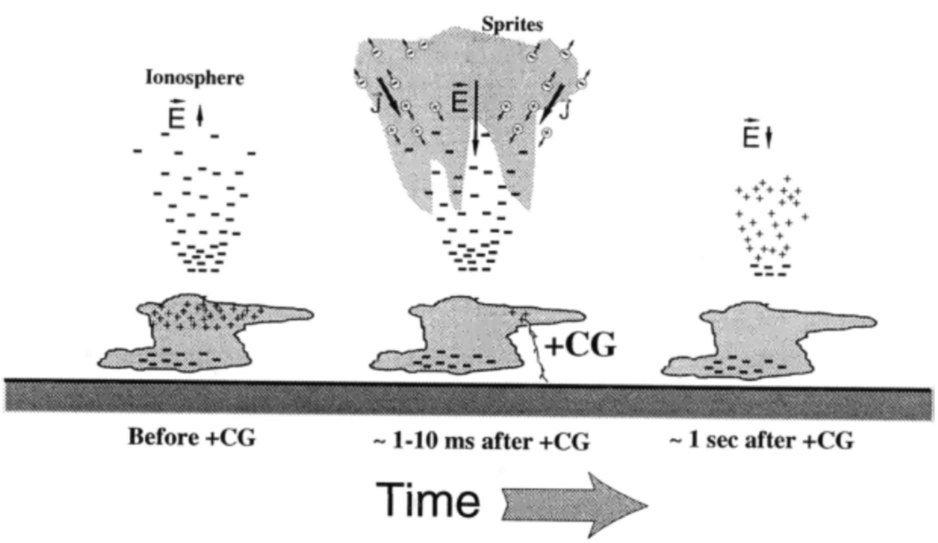


Figure 1.6: A timeline of sprite initiation. Adapted from Pasko [33].

Jet is an umbrella term for blue jets, blue starters, and gigantic jets, all of which are some tint of blue and discharge near the tops of thunderclouds in the stratosphere, below the regime of sprites. Despite being closer to lightning than their red counterparts, jets show no correlation with lightning. The rarity of jets has made it difficult to quantify features like their duration, but studies suggest that they last around 250 ms [20, 21, 35], longer than sprites and lightning. The distinguishing features between blue jets, blue starters, and gigantic jets are their terminal altitudes and sizes: blue jets terminate at 40-50 km while blue starters only reach about 25 km [21], and the term "gigantic jet" was coined after Pasko et al. [36] published photographic evidence of a blue jet that traveled with speeds on the order of 10^5 m/s and reached up into the ionosphere, showing sprite properties. We reprint the photo sequence in Fig. 1.7. It is generally agreed upon that the mechanism for jets is similar to that of lightning. More precisely, blue jets and starters are positive leaders that move upward and die in the thinning atmosphere [37]. Gigantic jets are +IC flashes that start from the main negative and punch through the upper positive region of a cloud; they become "gigantic" because the main negative region (which holds more charge than the upper positive region due to upper positive/ionospheric charge mixing) feeds the conducting leader as it rises [38].

Elves are expanding halos of light emanating from the ionosphere. They grow to be between 100 to 300 km in diameter before fading out and occur about 350 μs after high intensity CG discharges [39, 40]. The accepted mechanism for elves was first published in 1994 by U.S. Inan et al. [41], who claimed that atmospheric radio waves (known as sferics) emanating isotropically from CG discharges thermally excite particles in the ionosphere. The halo structure derives from the fact that the sferic intersecting the ionosphere is comparable to a sphere intersecting a plane, since the radius of the ionosphere is much greater than that of the sferic. In 1997, Inan et al. used an array of high-speed photometers to measure the propagation speed of two elves that occurred above the Yucca Ridge fields in Colorado; they present that the "apparent speed of lateral expansion of each of the two [elves] is $(3.1 \pm .8)$ times the speed of light, in good agreement with the original predictions," [42] where the predictions they refer to were published the previous year by Inan et al. [43].

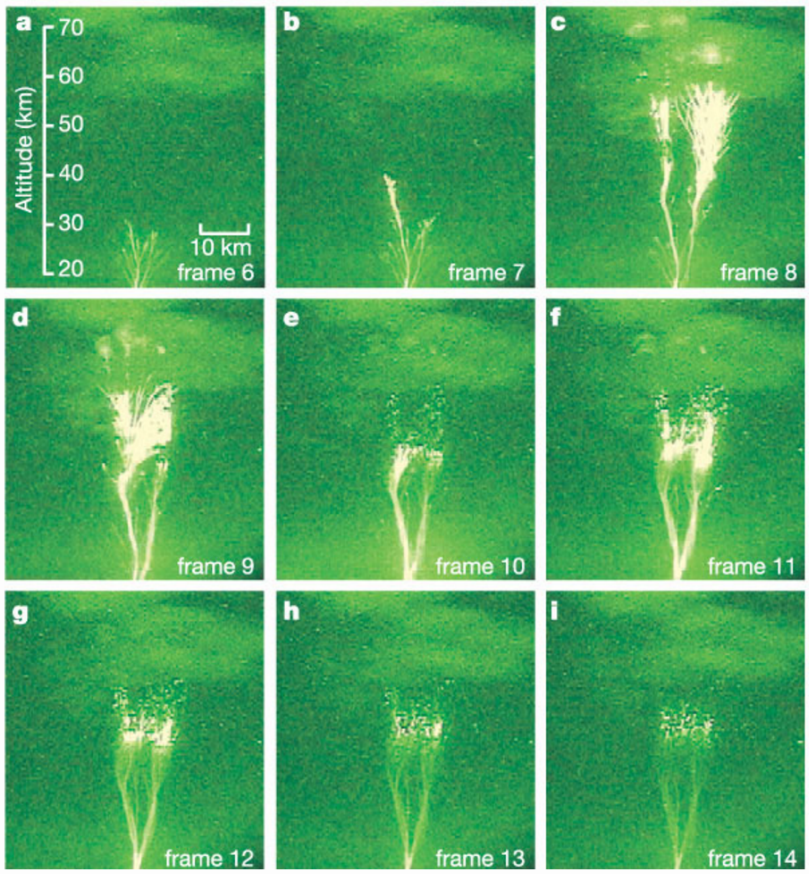


Figure 1.7: The first evidence of gigantic jets. From Pasko et al. [36].

The third category of AE – the GEC – pertains to the electrodynamics of the planet as a whole. The Earth and its ionosphere should be thought of as two conductors of an enormous spherical capacitor [44, 45], with leakage current between 1-2 kA [46] due to drifting ions in the middle atmosphere. A remarkable consequence of this is that the Earth experiences electric fields on the order of 10^2 V/m during fair-weather conditions (no thunderstorms) [45, 47]. Furthermore, S.J. Mauchly [48] provided the first convincing evidence that fair-weather electric fields vary diurnally, which indicates that the GEC couples to the sun [49]. This coupling is expected because solar wind particles and cosmic-rays are responsible for most of the ions in the atmosphere. Other less-obvious coupling mechanisms are discussed in detail by Tinsley [50].

Despite the neutralizing current of solar and cosmic ions, the Earth/ionosphere capacitor remains charged because thunderclouds act as perpetually charging batteries. The positive charges that accumulate at the top of these clouds drift through the ionosphere towards areas of fair-weather, and then fall to the Earth. We present an illustration of the process in Fig. 1.8. It is hard to overstate the importance of cloud electrification for the GEC. If it did not happen, the spherical capacitor would neutralize in tens of minutes [10].

We conclude our GEC discussion by pointing to current research that looks to quantify the connection between the GEC, the sun, and climate change. In 1990, C. Price and D. Rind argued that researchers would find a rise in AE due to global warming [51]. Various studies have since shown correlations between temperature and lightning activity [52–54], including one by N. Reeve and R. Toumi, who used the above-mentioned optical OTD data to show a correlation between global monthly land lightning activity and changes in global monthly land wet-bulb temperatures [55]. These studies suggest that AE will respond to global warming and therefore can play a role in quantifying global warming where temperature data are not readily available [56].

The fourth and final manifestation of AE is the TGF. TGFs are bursts of gamma-rays associated with IC lightning strikes. These bursts were first discovered in 1994 by the Burst And

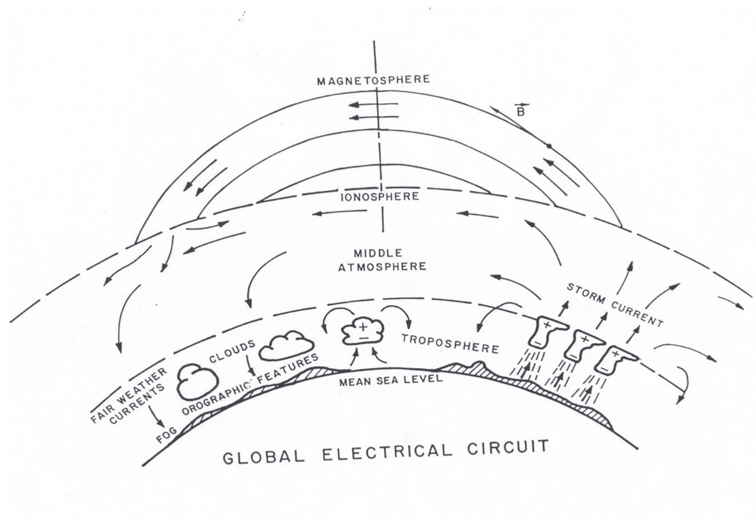


Figure 1.8: A simplified model of the GEC. From Roble and Tzur [57].

Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory [58], an experiment originally focused on cosmic gamma-rays. Surprisingly, BATSE found that high energy radiation was also coming from lightning storms on Earth.

It was first proposed that these gamma-rays were associated with red sprites, which were known to occur at higher altitudes [58, 59]. This was made under the assumption that the dense atmosphere would attenuate away photons produced below about 30 km above sea level. This assumption was only debunked more then ten years later, when J.R. Dwyer and D.M. Smith used Monte Carlo (MC) simulations to show that observed TGF gamma-rays must have initiated deep in the atmosphere, at altitudes corresponding to thunderclouds and IC lightning [60].

TGFs are most likely bremsstrahlung emissions from relativistic electrons accelerated in a cloud. The existence of these electrons was already predicted by C.T.R. Wilson in 1925 [61] and were named “runaway electrons” by A.S. Eddington in 1926 [62]. Wilson recognized that the Bethe-Bloch function, depicted in Fig. 1.9, predicts that, for a certain energy range, the frictional force of air on an electron decreases with the energy; thus one seed electron with enough initial energy

– e.g. a cosmic-ray secondary – can be accelerated to relativistic speeds, ionizing air molecules in its path. A fraction of the free electrons produced in the ionization run away as well, sparking an electron avalanche – called the Relativistic Runaway Electron Avalanche (RREA) – not unlike the well-known Townsend avalanches that drive old radiation detectors.

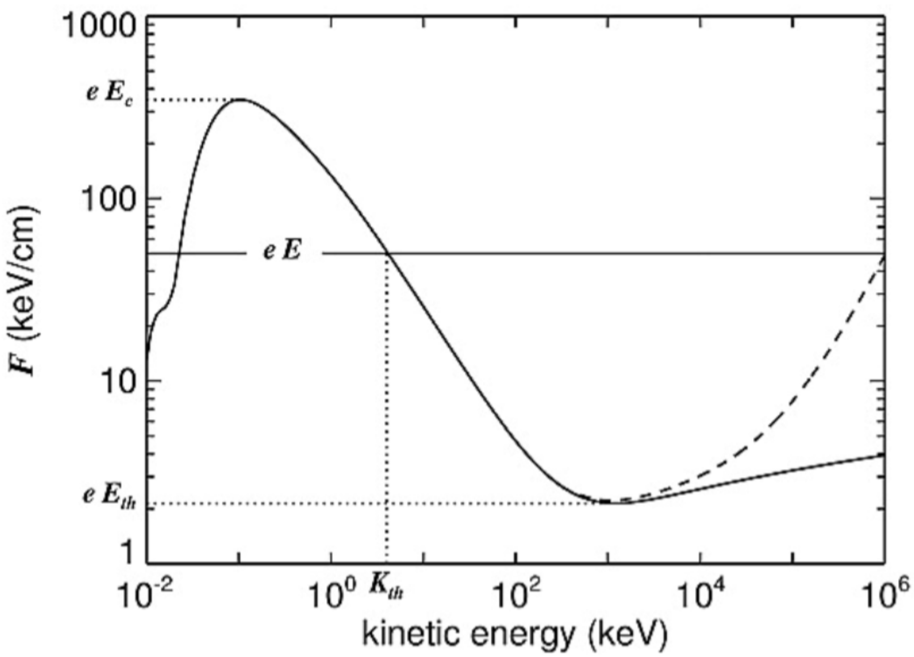


Figure 1.9: The effective frictional force of air on a free electron as a function of the electron's kinetic energy, more generally known as the Bethe-Bloch function. The solid line only accounts for inelastic scattering of the electron with air molecules while the dashed line also includes bremsstrahlung losses. The horizontal line shows the force due to a constant electric field $E = 50\,{}^{\mathrm{kV}}/_{\mathrm{cm}}$ on an electron with charge $-e$. Hence, runaway electrons must have initial energy $K > K_{th}$. For an electric field $E > E_c$, electrons run away regardless of their energy (cold runaway), and E_{th} is the minimum electric field necessary to produce any runaway electrons at all. From Dwyer [63].

Wilson further suggested that some of these electrons could burst out of the sky, follow one of the Earth's magnetic field lines and then precipitate back into the atmosphere. This caught the attention of astrophysicists who were concerned that their observations of high energy cosmic-rays might have been affected by particles of terrestrial origin. Numerous research groups used balloons, Geiger counters, and scintillator detectors to verify the existence of these electrons, with little success [64–66]. While the theoretical development and experimental search for Wilson's "runaway electrons" continued throughout the 1920's and into the 1970's, nobody could confirm the runaway mechanism in part due to the difficulty of constraining the background count rates produced by cosmic-rays and, for ground-based experiments [67], radioactive aerosols washed out of the atmosphere during rainfall [68]. The offending aerosols consisted primarily of radon and so the background was dubbed "radon washout."

The first compelling evidence for relativistic runaway came in the 1980's, when McCarthy and Parks [69] measured bremsstrahlung x-rays while flying through a thunderstorm with a NASA F-106 aircraft. Gurevich et al. [70] were the first to point out that Wilson's theory could explain the fluxes measured by McCarthy and Parks and also recognized that RREA would place an upper limit on the electric field in air to be an order of magnitude lower than the breakdown threshold. This – the reader recalls – was consistent with electric field measurements [3]. Thus Gurevich et al. solved two problems with one ansatz, the production of RREA.

Four years later, balloon-based x-ray measurements taken by Eack et al. [71] showed fluxes that were unexplainable by avalanche multiplication by a single seed electron. Gurevich suggested that multiple cosmic-ray seeds must have made more avalanches, but an opposing theory was advocated by J.R. Dwyer [72, 73], who argued that Gurevich's treatment of the system was too simple. In particular, Dwyer theorized that backscattered x-rays and positrons, which were neglected by Gurevich, travel against the avalanche before ionizing air molecules. With MC simulations that modeled elastic scattering, bremsstrahlung, Compton scattering, and pair production, Dwyer recognized that these backscattered x-rays and positrons play a crucial role in amplifying RREA.

Dwyer's simulations were corroborated five years later by Babich et al. [74], but the field is still undecided on how RREA works. For instance, while Gurevich and Dwyer use models of large electric fields over radial distances of hundreds or even thousands of meters, a new theory by Celestin et al. [75] suggests that tips in front of lightning leaders, with sizes on the order of centimeters, see enough field enhancement for cold runaway (no seed electron required) to occur. This is remarkable because it would directly connect TGFs to lightning, whereas the Gurevich and Dwyer approach posits RREA as a related but all-together separate discharge mechanism for clouds.

These competing theories have not been interrogated to levels that might render one falsified. This is in part due to a lack of data. Hence multiple experimental campaigns have been launched in the last two decades to discover more TGFs from the ground [76] and weather planes [77]; expensive satellite missions tend to be motivated by astrophysics research, but multiple low Earth orbit gamma-ray detectors actively supply TGF data [78, 79].

The first satellite mission to provide TGF data after BATSE was the Reuven-Ramaty High Energy Solar Spectroscopic Imager (RHESSI) [80]. RHESSI scientists correlated TGFs to IC lightning strikes [60] and produced the first diurnal distributions of TGFs [81]. This research relied on the Grefenstette catalog of RHESSI TGFs, which uses a search algorithm that triggers on Poisson outliers in the count rate [82]. The algorithm is therefore biased against TGFs that happen during detector paralysis and so disregards the possibility that a TGF itself might paralyze the detectors.

This last point motivates the following thesis work. We claim that there exist RHESSI-paralyzing TGFs (RPTs). We present a catalog of candidate RPTs and maintain that the candidates originate from thundercloud RREA as opposed to cosmic sources. We argue this by (1) indicating TGF properties in the time series of the candidates and (2) demonstrating a correlation between the candidates with both WWLLN lightning radio sferics and the Grefenstette catalog of standard TGFs.

2 Methods

We briefly introduce the specifications of RHESSI most pertinent to our analysis: its gamma-ray sensitivity, its behavior under saturation, and its reset procedure. A more complete review of RHESSI's technology can be found in Smith et al. 2003 [83]. Then we explain the RHESSI data structure and the Paralyzing TGF Search Algorithm (PTSA).

RHESSI uses 9 coaxial germanium crystals to measure photon energies ranging from 3 keV to 17 MeV [83]. Each crystal is split into front and back segments, and every segment has its own readout electronics, such that each crystal is a pair of two detectors. The front segments point at the sun and are optimized to measure hard solar x-rays (energies up to 100 keV), while the back segments measure solar gamma-rays and TGFs (up to 17 MeV). The detectors have a full width half maximum energy resolution ≤ 1 keV at 3 keV, which increases to ≈ 5 keV at 5 MeV, and have binary microsecond time sensitivity (i.e. $1/1024^2$ s) [80, 83].

The spectrometer experiences saturation if greater than 17 MeV of energy is deposited in one of its detectors within one binary microsecond. When this happens, a so-called Upper Level Discriminator (ULD) circuit triggers, which stops the electronics from attempting to measure the associated energy and minimizes the consequent dead time. In fact, the ULD dead time is relatively negligible (≈ 2 μs). We emphasize that a count flagged as a ULD, while indeed only one count, may not be one particle with energy greater than the 17 MeV threshold, but instead a group of coincident particles with total energy greater than the threshold. We show a ULD in Fig. 2.1.

With respect to non-negligible RHESSI dead time, Grefenstette et al. point out that "if the time between two counts in a detector is less than .84 μs ... then a single count is recorded with an energy that corresponds to the sum of the energy of the two original counts. If the time between two counts is greater than .84 μs but is less than 5.6 μs, then the arrival of the second count contaminates the processing of the first count and both counts are vetoed... [and] if the time between two counts is greater than 5.6 μs but less than 9.6 μs, then the first count is recorded but the second count is vetoed." [82]. This elaborate vetoing procedure minimizes the effects of detector pileup, which is when a detector mistakenly measures counts to be of high energy because of high count rates. From the above, we see that RHESSI only experiences pileup when counts occur within .84 μs of each other. Moreover, the preamplifiers used for readout contain "pulsed reset circuits" [84], which reset whenever a detector measures 40 MeV of energy over any period of time. The associated dead time is 40 μs [83]. Resets can also trigger fictitious ULDs (ULDs which do not correspond to any measurement), but this effect is not yet well-quantified.

RHESSI's dead time behavior motivates us to introduce new nomenclature. RHESSI is *saturated* when it is counting at or near its maximum count rate, which corresponds to 30-70% dead time. This definition implies that most TGFs that RHESSI detects also saturate RHESSI during their peak 50 μs [82]. RHESSI is *paralyzed* when it is not measuring counts at all – that is, if RHESSI only documents resets and ULDs. The distinction between saturation and paralysis is important for this work because RHESSI-saturating TGFs can still trigger conventional TGF algorithms, which rely on Poisson outliers in the count rate, but RPTs will lower the count rate significantly and therefore require a different search approach.

We produce a catalog of RPTs by searching the RHESSI data structure from 2010-05-03 to 2012-01-16. The data structure is organized so that every count is saved as an object with properties (e.g. time-of-measurement, detector number). One property is a boolean flag which is true if the count is a ULD. For the PTSA, the relevant properties are the time, detector number, energy, and ULD flag. With respect to the time window we search (2010-05-03 to 2012-01-16), we point out that RHESSI is "annealed" (heated dramatically and then cooled slowly) periodically to improve detector performance, and so we choose a time window in which RHESSI was in between two annealing periods. From now on we refer to the time window as the inter-anneal period.

Having described RHESSI and its data structure, we now present the PTSA. First, we call the inter-anneal data in one minute intervals. We apply a clock correction [82] and consolidate counts within one binary microsecond of each other. We drop < 30 keV counts, which primarily correspond to solar x-rays, and then define Medium Energy Counts (MECs) as anything between 30 keV and 600 keV. We then split these one minute sections into fifteen four second intervals for further analysis.

For each four second interval, we bin the ULD counts into 100 μs bins, and check if any bin satisfies all of the following criteria:

- There exist at least 5 ULDs and they span a time of greater than 15 μs. The time requirement discriminates against high energy cosmic-rays, which tend to manifest as coincident ULDs.
- The previous 2 ms has a mean count rate of less than 5 cts/ms, because we do not want to consider times when the background is significantly higher than RHESSI's mean (2 cts/ms) [82].
- There exist at least seven MECs within 300 μs after the 5 ULDs. For a ULD that occurs after the main 5 ULD segment, we drop all MECs within 5 μs of that ULD.

The bins that pass these criteria are the candidate RPTs. To make sure we did not lose any RPTs that were at the borders of the bins, we shift the bins by 50 μs, recheck the criteria, and consolidate a list of candidates.

Next we veto candidate RPTs whose counts are primarily in one or two detectors. This is because each detector occasionally experiences bursts of noise, which can falsely trigger the third item in the above criteria. We show an example of this kind of noise in Fig. 2.1. For the veto, we bin the MECs into a histogram based on their detector number d_i ($i = 1, 2, ..., 9$). We sort the histogram by the number of counts n_i in each detector, and call the new sorted detectors $\tilde{d}_i$ and counts $\tilde{n}_i$ (e.g. $\tilde{d}_1$ is the detector that measured the most amount of counts $\tilde{n}_1$). We calculate $\sum_i \tilde{n}_i \tilde{d}_i^2$ and require it to be greater than 1.5, a number we chose by testing the veto algorithm on multiple single detector noise bursts.

After the list is finalized, we check to see if any lightning radio sferics detected by the World Wide Lightning Location Network (WWLLN) [85–87] are coincident with the candidates. We say a candidate has a WWLLN storm match if 8 WWLLN triggers occur within 600 km and 10 minutes of the candidate, and we say a candidate has a WWLLN flash match if 1 WWLLN trigger occurs within 800 km and 1 second of the candidate.

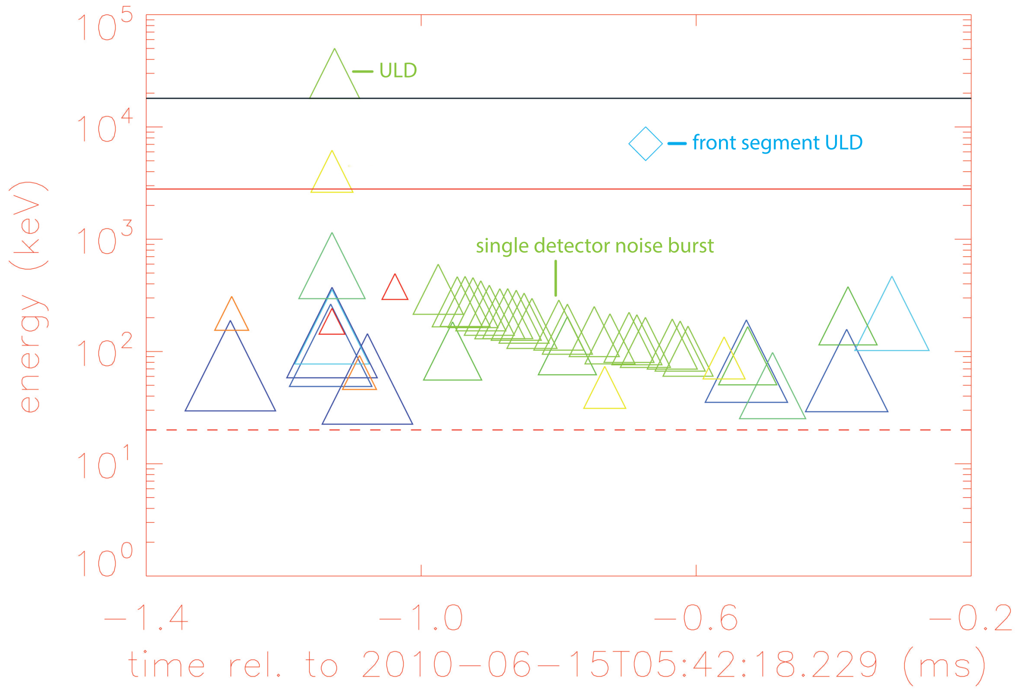


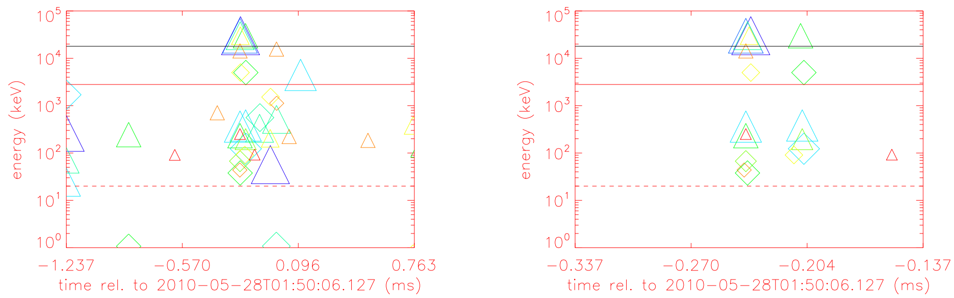
Figure 2.1: An example time series, which shows a single detector noise burst, a ULD, and a front segment reset. The triangle (diamond) symbols represent counts in the rear (front) detectors. Each symbol's color and size refers to its detector. (The differing sizes are useful for distinguishing counts of equal energy and time.) The two solid lines correspond to thresholds: front segment ULDs occur at 5 MeV (above the solid red line) and rear ULDs occur at 30 MeV (above the solid black line), and front and rear resets occur at 60 MeV (above the solid black line). Note the front segment ULD was added in ad hoc for the sake of demonstration.

3 Results

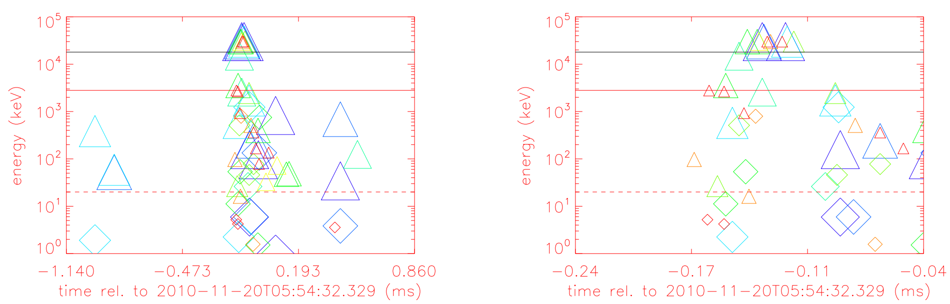
In this section we present the PTSA output and discover that it contains a set of false positives triggered by cosmic-rays. Fortunately, the false positives are easily distinguished from true RPT candidates, and so we remove them from the candidate list. We then present the dates, locations, time series and other relevant attributes of the leftover candidates.

The PTSA's false positives are caused by RHESSI measuring multiple cosmic-rays coincident with enough MEC background to trigger the algorithm. We show the 2 ms and 200 μs scale time series of a cosmic-ray event and a true RPT candidate in Fig. 3.1. The cosmic-ray/RPT distinction is lost in the 2 ms window but clear in the 200 μs window, where the cosmic-ray series shows two discrete columns characteristic of two high energy cosmic-rays scattering in multiple detectors upon arrival. On the other hand, the RPT series shows a continuous burst of ULDs expected from gamma-rays with different arrival times.

Using the distinction discussed above, we remove cosmic-ray events and present the true candidate RPTs in Table 3.1. The table shows their date, latitude, longitude, WWLLN storm flag, and WWLLN flash flag. The exact TGF position is unknown, and so the presented longitude and latitude values are the spacecraft's coordinates. The errors on the satellite positions are negligible for our purposes. We show time series of all the candidates in Fig. 3.2 and Fig. 3.3. There are two time series for each event, one with a 2 ms full scale and another with a 200 μs full scale.



cosmic-ray

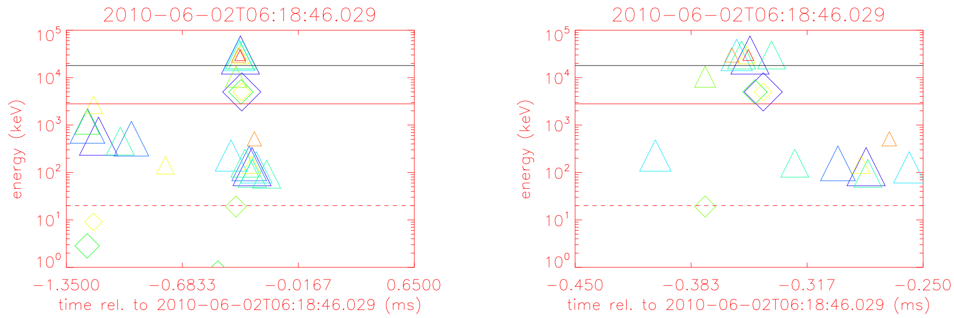


RPT candidate

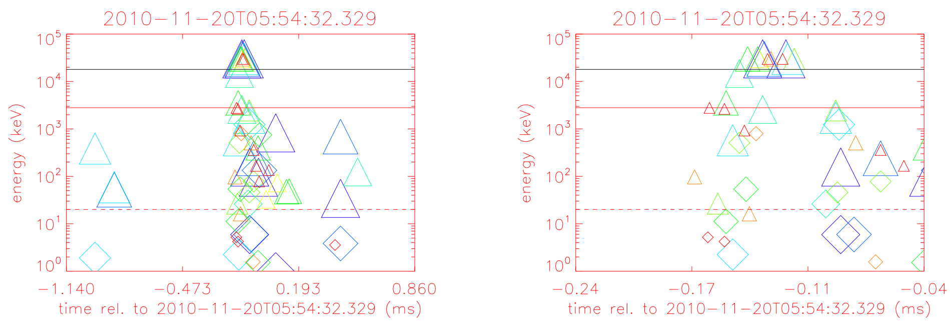
Figure 3.1: Time series of a cosmic-ray false positive (the top) and a true RPT candidate (the bottom). We show a 2 ms (200 μs) time window on the left (right). The cosmic-ray is identifiable by the discrete pulses found in its 200 μs window time series found on the top right (see text).

Candidate	Date (YYYY-MM-DDTHH:MM:SS.SSS)	Latitude (degrees)	Longitude (degrees)	storm	flash
1	2010-06-02T06:18:46.029	-7.43	98.8	0	1
2	2010-11-20T05:54:32.329	-3.05	9.2	1	0
3	2010-12-05T03:52:29.684	-2.75	110.	1	1
4	2011-02-10T03:14:41.465	-2.61	21.3	1	1
5	2011-02-13T15:00:45.942	-4.72	10.4	1	1
6	2011-08-04T03:09:38.320	-4.05	92.6	1	1
7	2011-10-05T03:41:09.046	0.02	14.5	1	0

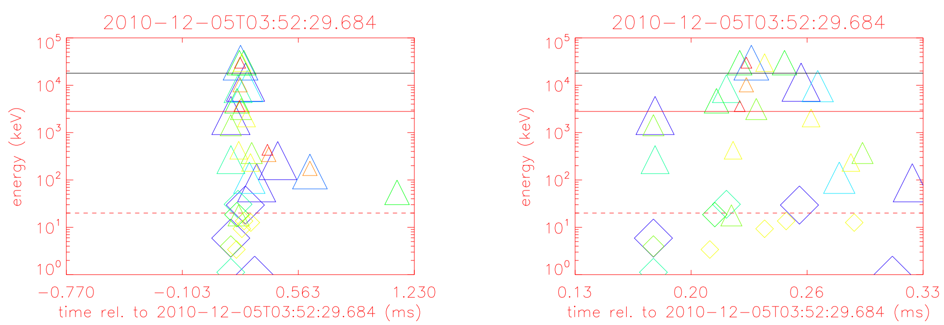
Table 3.1: The catalog of candidate RPTs. The storm column shows “1” if 8 WWLLN triggers occur within 600 km and 10 minutes of the candidate, and the flash column shows “1” if 1 WWLLN trigger occurs within 800 km and 1 second of the candidate (else they show 0).



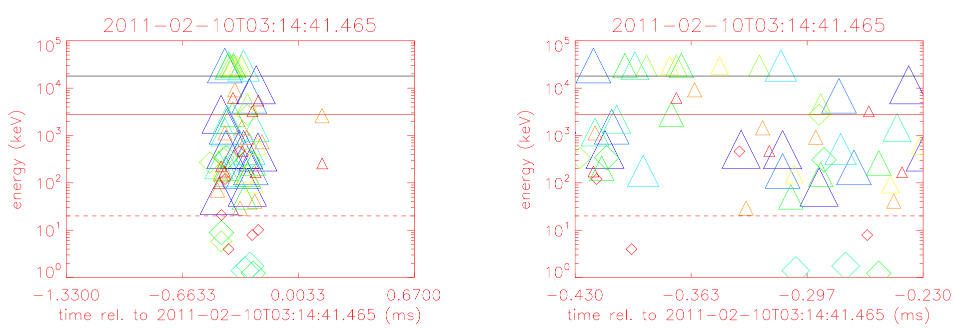
Candidate 1



Candidate 2

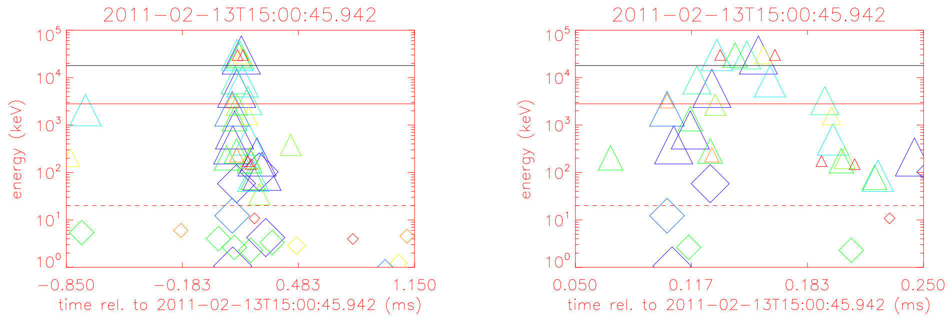


Candidate 3

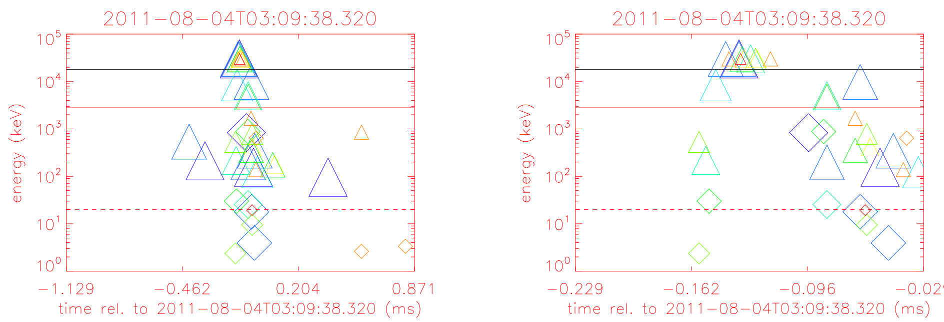


Candidate 4

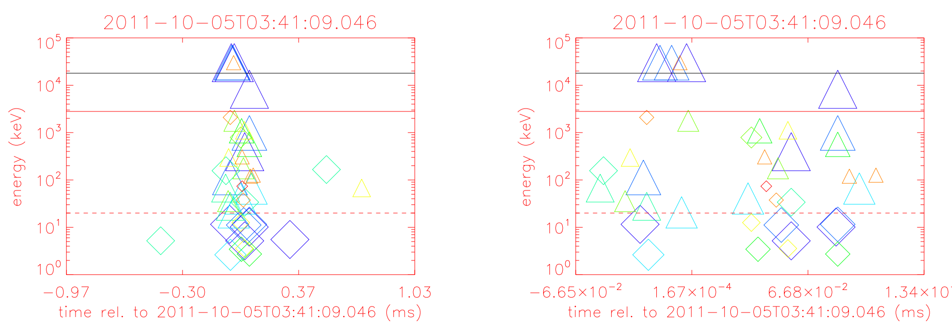
Figure 3.2: Time series of RPTs 1-4, with the 2 ms (200 μs) time window on the left (right).



Candidate 5



Candidate 6



Candidate 7

Figure 3.3: Time series of RPTs 5-7, with the 2 ms (200 μs) time window on the left (right).

4 Discussion

In this section we discuss the rise and fall of the fluxes and energies found in Fig. 3.2 and Fig. 3.3, and suggest that they correspond to the RREA mechanism and atmospheric Compton scattering, respectively. Then we show three random distributions for three test-statistics – the WWLLN storm match rate, the WWLLN flash match rate, and a seasonal/geographical "inner product" with the Grefenstette catalog of TGFs – and show that the candidates fail to come from random distributions with a confidence of greater than 98%.

With the exception of candidates 1 and 4, all candidates show a rise in mean energy with time before the period of paralysis. This is not expected from the avalanching in RREA. Instead, Dwyer [73] predicts that the gamma-ray *count rates* should rise to a maximum with rise times ranging from tens of μs to 1 ms. Since the rise-times shown in Fig. 3.2 and Fig. 3.3 are comparable to those values, we speculate that the rise in mean energy might be due to pileup in the detectors. Dwyer does not account for atmospheric propagation in his rise-time calculations, but it is expected that atmospheric Compton scattering would lengthen and modulate the energy ascent. Quantifying the effect of pileup and modulation is left for future work.

We see the effect of atmospheric scattering more clearly after RHESSI's paralysis. TGF gamma-rays that scatter in the atmosphere should arrive later and be less energetic than their unscattered counterparts. Hence we expect a falling tail of counts in the time series. To check this, Celestin and Pasko [88] simulated the propagation of 25×10^6 photons following a TGF energy spectrum proposed by Dwyer [89]; the photons emanated from an altitude of 15 km isotropically within a 45° angle about the vertical axis and departed at the same time. We reprint their results next to an RPT from outside the inter-anneal period in Fig. 4.1. If only in a qualitative sense, the tail shown in Fig. 4.1 shows similarities to the structure in the candidates' time series.

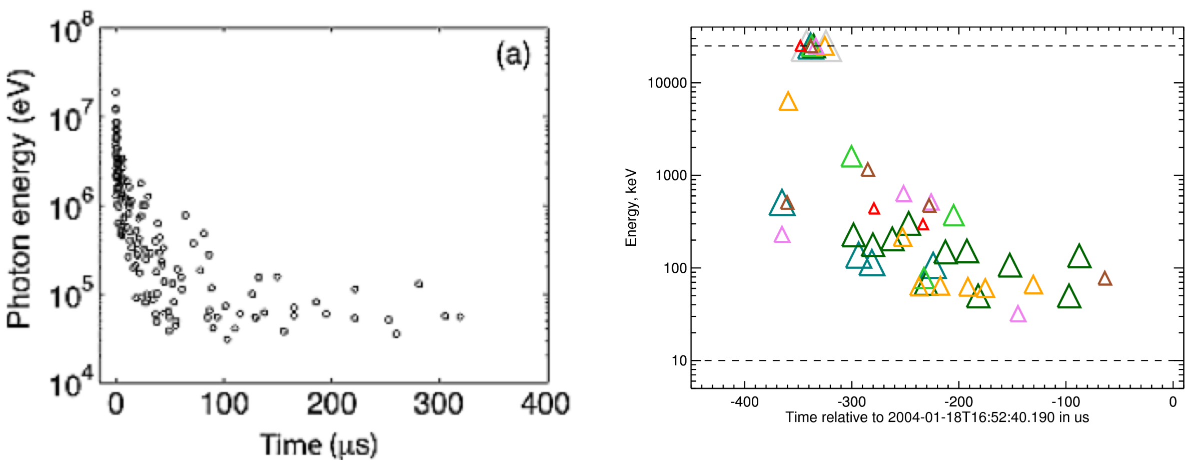


Figure 4.1: Left: A simulated time series of 25×10^6 gamma-rays that departed an altitude of 15 km isotropically, within a 45° angle, and at the same time. The initial photon energies follow a distribution proposed by Dwyer [89]. The simulation accounts for gamma-ray Compton scattering in the atmosphere. Right: An RPT from outside the inter-anneal period.

Next we generate 1000 random dates within the inter-anneal period and produce distributions for the WWLLN storm match rate (henceforth referred to as STORMQF) and WWLLN flash match rate (FLASHQF). We show the distributions in Fig. 4.2 and Fig. 4.3. The null-hypothesis (that the candidates are random dates) is broken with a p-value of .02 and less than .001 respectively, where we assume the errors on our empirical distributions are negligible.

It is remarkable that the candidates under-perform the Grefenstette catalog in STORMQF, but outperform the Grefenstette catalog in FLASHQF. This might be expected if TGFs are intimately connected to lightning propagation, as in Celestin's theory mentioned above [75]. A more energetic RREA would correspond to a more detectable radio-sferic.

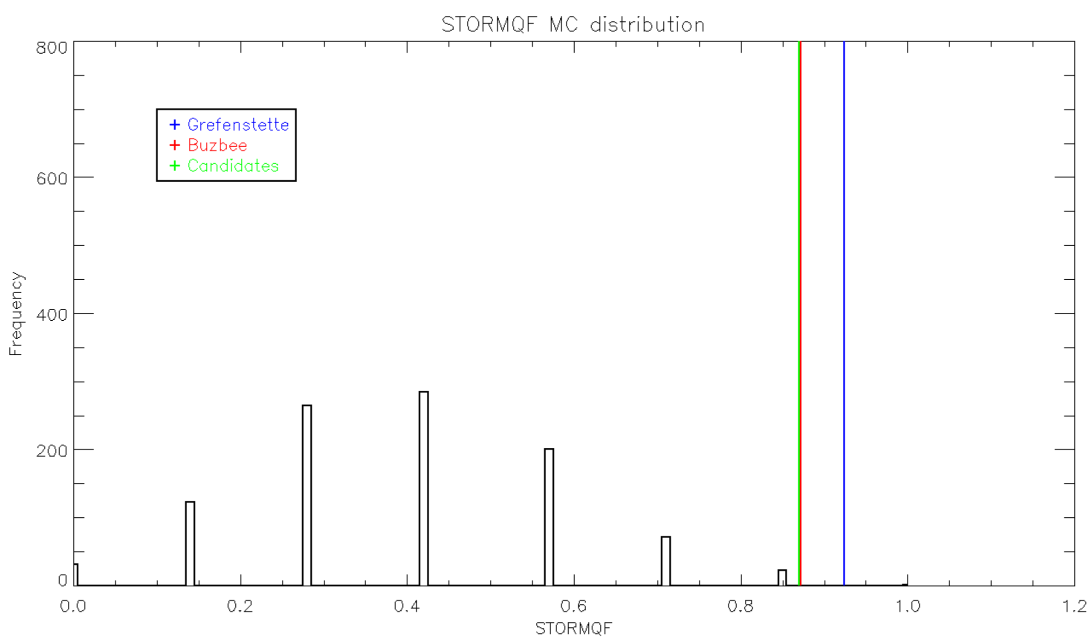


Figure 4.2: Empirical distribution of STORMQF from 1000 random catalogs of 7 dates in the inter-anneal period. The STORMQF values for the Buzbee, Grefenstette and candidate catalogs are plotted as vertical lines.

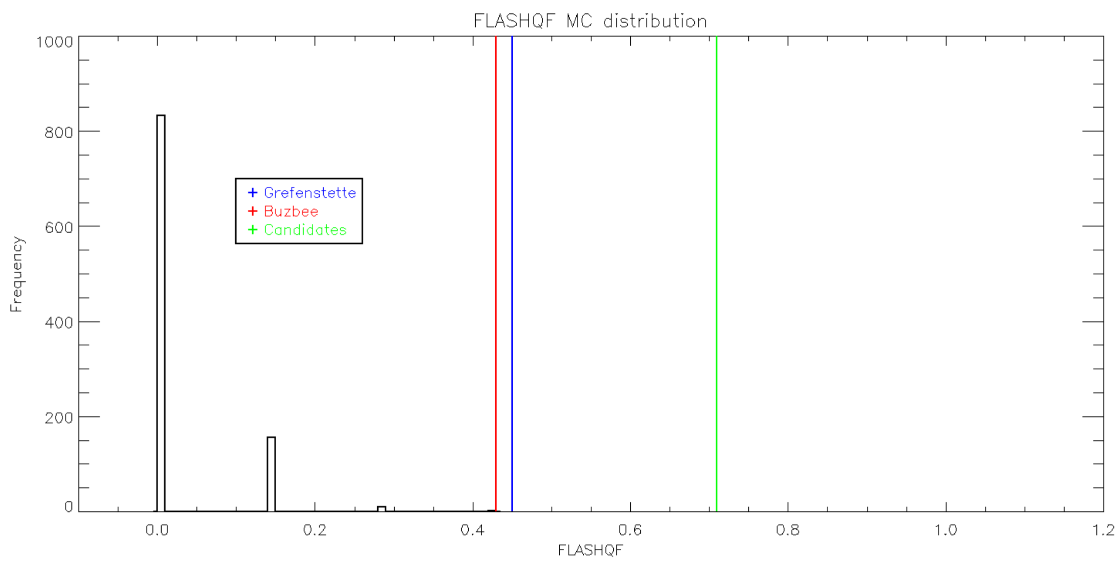


Figure 4.3: Empirical distribution of FLASHQF from 1000 random catalogs of 7 dates in the inter-anneal period. The FLASHQF values for the Buzbee, Grefenstette and candidate catalogs are plotted as vertical lines.

As a third and final MC argument, we produce an empirical distribution for a parameter called MAPQF. In words, MAPQF is the average amount of Grefenstette TGFs that are geographically and monthly equivalent to the TGFs in a test catalog. We calculate this by counting how many Grefenstette TGFs are within ±1 month, ±3° latitude, and ±3° longitude of each event in the test catalog, summing those, and then dividing by the number of TGFs in the test catalog. In other words, if there are G_i Grefenstette events equivalent to the i^{th} test catalog event, and there are n test-catalog events in total, then we calculate

$$\text{MAPQF} = \frac{1}{n}\sum_{i=1}^{n} G_i. \tag{4.1}$$

We show the MC distribution for MAPQF in Fig. 4.4. None of the 1000 random catalogs receive a MAPQF value greater than that of the candidate, Buzbee or Grefenstette catalogs.

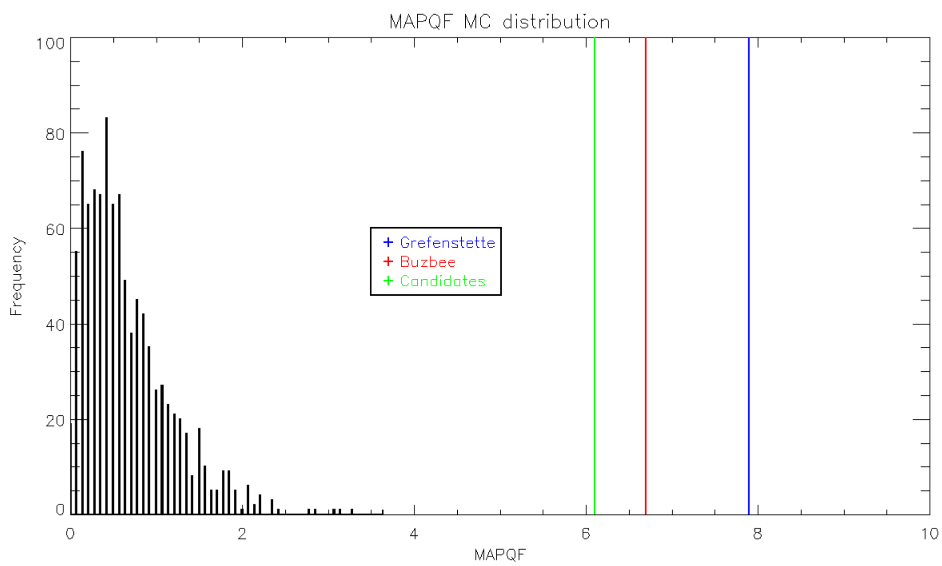


Figure 4.4: Empirical distribution of MAPQF from 1000 random catalogs of 7 dates in the inter-anneal period. The MAPQF values for the Buzbee, Grefenstette and candidate catalogs are plotted as vertical lines.

5 Conclusion

We generated a list of candidate RPTs and showed that their time series have a geometry that is potentially expected from RREA and atmospheric Compton scattering. We consider this as qualitative evidence for the validity of the candidates as TGFs. Furthermore, we presented three quality factors (STORMQF, FLASHQF, and MAPQF) to measure the legitimacy of a TGF catalog, and showed that if the list of RPT candidates was in fact a list of random dates, it would have performed as well as it did less than .1% of the time for FLASHQF and MAPQF, and less than 2% of the time for STORMQF, where we assumed the errors in our empirical distributions are negligible. These findings suggest that we have discovered a new subclass of bright TGFs; RPTs are missed in other RHESSI search algorithms due to the algorithms' bias against times when RHESSI is in paralysis.

The next step in RPT research is to find more RPT candidates by running the PTSA on times in the RHESSI data outside of the inter-anneal period. Also, a more quantitative approach to linking the candidates' time series to RREA and atmospheric Compton-scattering is in order, and further comparing RPT time series with the MC simulations from Celestin and Pasko should be fruitful [88]. With respect to the MC methods that we present in this thesis, the fact that the RPT candidate catalog produces p-values of less than 2% for three somewhat-independent quality factors suggests that the true p-value for these RPTs breaking the null-hypothesis is in fact less than 2%. Future researchers should empirically quantify how independent the three quality factors are and then put a more precise confidence on the legitimacy of the RPTs.

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