Terrestrial Gamma-ray Flashes and Other High Energy Atmospheric Phenomena: An Overview

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Review Paper:

Terrestrial Gamma-ray Flashes and Other High Energy Atmospheric Phenomena: An Overview

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Abstract

Extraordinarily bright events with highly energetic radiation in the form of bursts of hard X-rays and γ-rays of short durations have been detected in our atmosphere by scientific community routinely during strong thunderstorms and lightning activity. Terrestrial Gamma-ray Flashes (TGFs) are very short (< 1 ms) bursts of highly energetic gamma-ray photons which are generated during powerful thunderstorms and have been detected by both airborne as well as ground based experiments. TGFs driven source has been an active area of research since their accidental discovery by Burst and Transient Source Experiment detector, on board the Compton Gamma-ray Observatory in 1994. These gamma-rays bursts originate in deep atmosphere within thunderclouds typically at altitude ranging from 10-20 km. It is found that certain meteorological conditions like high convective available potential energy (CAPE) values, high cloud tops, high lightning stroke occurrence and vigorous electrically active storms play important role for TGF production.

It is believed that rapid production of relativistic runaway electrons which are accelerated in the strong thundercloud/lightning electric field causes TGFs via bremsstrahlung emission. Gamma-ray glows or Thunderstorm Ground Enhancements (TGEs) and TGF afterglow are also some other high energy atmospheric phenomena which are related to TGFs. In this study, we will discuss about the characteristics of TGFs, Gamma-ray glows or Thunderstorm Ground Enhancements (TGEs) and TGF afterglow including energy spectrum, time profile, their correlation with lightning and their production mechanisms.

Keywords: Lightning, Thundercloud, Terrestrial Gamma-ray Flashes, Thunderstorm Ground Enhancements, TGF afterglow, Bremsstrahlung Emission.

Introduction

Thunderstorms and lightning are well known natural particle accelerators[36]. They generate many electrical atmospheric phenomena in Earth's atmosphere of time scale ranging from sub-microseconds to tens of minutes. Terrestrial gamma-ray flashes (TGFs) and its related phenomena like Gamma ray Glows or Thunderstorm Ground Enhancements (TGEs) and TGF afterglow are some of them. It is believed that these high energy phenomena are the result of the interaction of high energy particles with the air molecules (Nitrogen and Oxygen) in the presence of strong electric fields of charged thunderclouds and lightning.

Previous observations reported that they occur in the form of fluxes of γ-rays, electrons, positrons and neutrons[22]. It has been discovered that particle fluxes carry a lot of information on the parameters of atmosphere for example γ-ray flux and electron flux carry the information of net potential in the atmosphere related to the positive and negative charged layers of thundercloud.

However, the charging process of thunderclouds, initiation of lightning and its relation with TGFs, TGEs and TGF afterglow are poorly understood and still remain a great puzzle for scientific community. Such high energy atmospheric phenomena were observed only in the last decade of the 20th century. A concrete mechanism of these phenomena, production and propagation of associated energetic radiation and their effects on atmospheric electrodynamics are beyond our current understanding and remain a part of debate. In this study, we will review a few high energy atmospheric phenomena such as TGFs, TGEs and TGF afterglow.

Terrestrial Gamma-ray Flashes

Terrestrial gamma-ray Flashes (TGFs) are natural occurring extraordinarily bright and brief (<1 ms) bursts of energetic photons (0.1-100 MeV) which are associated with strong thunderstorms and lightning activity[9,44,73,98,106]. They have been observed by various airborne and ground based experiments. TGFs were serendipitously first discovered almost 26 years ago by Burst and Transient Source Experiment (BATSE) on NASA's Compton Gamma-Ray Observatory (CGRO), a NASA satellite in low earth orbit devised to observe cosmic gamma-ray bursts from outer space[44]. TGFs have since been observed by other experiments on satellites Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI)[98], Astro-Rivelatore Gamma a Immagini Leggero (AGILE)[73], Fermi Gamma-ray burst Monitor (GBM)[9] etc.

More recently, TGFs were detected by the relativistic electrons (RELEC) experiment on the Vernov satellite[7]. TGFs are mostly associated with the initial stage (during propagation of stepped leader) of the moderately strong positive intracloud (+IC) lightning[26,84,97,104,115] which is the most frequent type of lightning discharges in the Earth's atmosphere. TGFs are also correlated with stepped leader of cloud-to-ground lightning and observed using ground based experiments[1,12,54,61,93,102]. Tran et al[109] using ground based experiment observed a 6 pulses TGF (two pulses had energy more than 5.7 MeV) of duration 16 µs and was associated with single stroke negative cloud-to-ground (–CG) lightning.

The TGF began 191 µs after the return-stroke (peak current 224 kA) electric field peak. TGFs were also observed by detection of distant radio signals on the ground[71]. The temporal profiles of TGFs consist of one or sometimes several pulses[44,45]. TGFs pulses are found either symmetrical or asymmetrical[45]. Most of the asymmetrical TGF pulses are found to have faster rise times than fall times. The median rise time for asymmetric pulses is found ∼3 times shorter than for symmetric pulses while their fall times are comparable[45]. Furthermore, the fastest rise time was observed 7 µs, which sets an upper limit on the source radius of about 2 km[9].

In addition, Foley et al[45] presented the rigorous analysis of temporal properties of a large sample of 278 TGFs. They showed that at least 67% of TGFs at satellite altitudes are significantly asymmetric. Symmetric and asymmetric pulses can be fitted into Gaussian and lognormal functions respectively[9]. Recently, two TGF events were recorded at ground level in China, when the return strokes of a nearby negative CG lightning flash occurred[64]. According to their observations, the first gamma-ray burst had a duration of 563 µs and the second one had a duration of 353 µs. The time interval of the two bursts was noted 76.2 ms. TGFs act as a powerful natural accelerators which accelerate particles (electrons and positrons whenever they are produced by pair production process) and generate radiation up to hundreds of MeV energies[107].

Tavani et al[107] measured the number ratio of TGFs over normal lightning in tropical regions and found to be nearly 10^{-4}. TGFs emit a fluence of ~1 photon/cm^2 and have harder energy spectrum (each emitted photon of TGFs has the highest average energy). TGFs exhibit both spatial and temporal correlations with lightning activity. The average delay between the lightning and the associated TGF was found −0.77 ms, suggesting that the TGFs occur prior to the lightning discharge and are thus likely to be generated during the initial stages in the development of a lightning discharge[24]. TGFs are now expected to be produced within the thunderstorm and are associated with lightning discharges. Smith et al[98] with RHESSI satellite observed that TGFs are so bright and may have energy up to 20 MeV.

Briggs et al[9] observed 12 TGFs from the GBM and found typical maximum energies for most of the TGFs around ~30 MeV with one TGF having a 38 MeV. Marisaldi et al[73] reported the detection by the AGILE satellite of TGF photons of energy up to 40 MeV. They sometimes saturate detectors on spacecraft hundreds of kilometres away. As the gamma-rays in TGFs propagate up, they generate energetic secondary electrons and positrons via pair production and Compton scattering that are detected by spacecraft in the inner magnetosphere[10].

It is generally believed that these gamma-rays are generated due to the bremsstrahlung, by energetic runaway electrons that are accelerated in the presence of large electric fields in the atmosphere during thunderstorms/lightning. It has also been proposed that the large number of runaway and secondary electrons involved in TGFs also radiate energetic radio signals[25,37] with amplitudes comparable with conventional lightning discharges. TGFs are also associated with lightning currents, is now well known. The quantitative analysis of lightning signals associated with 54 TGFs has been done and it is found that the peak currents of TGF-associated lightning discharges vary between <10 kA to 270 kA[69]. Majority of TGFs (85%) were associated with lightning discharges with peak currents <70 kA.

Moreover, the lightning discharges with peak currents >70 kA were only associated with TGFs observed at latitudes below 23°, namely over tropical storms. All the TGFs in their database were related to the lightning charge moment changes between <+10 C km and +200 C km, with a mean value of +64 C km. It has been found that TGFs longer than 210 µs are associated with lightning currents below 10 kA, TGFs those lasting from 90-210 µs range are from 80-35 kA and the shortest TGFs are associated with currents above 150 kA[25].

According to Lu et al,[70] the gamma-rays in TGFs are typically produced by upward negative leader during the initial stage of normal intra-cloud (IC) lightning that creates a considerable charge moment change within several milliseconds. Further, they observed that that peak current of TGF-related discharges could be as high as >+500 kA and the associated charge transfer is typically >+20 C km. When TGFs were first reported, it was suggested that these intense radiation are closely associated with red sprites or other high altitude (>30 km) discharges. High altitude discharges include red sprites, blue jets, blue starters, halos and elves which occur from the top of the thunderclouds to the lower ionosphere[87].

However, spectral measurements by (RHESSI) spacecraft and accompanying modelling work have shown that the TGFs originate from altitudes <21 km in the atmosphere within the range of thunderstorms top which is too low for sprites and other high altitude discharges[13,32]. In addition, Cummer et al[26] observed and analysed the 30 kHz radio emissions from lightning discharges and found that 13 of the RHESSI TGFs were associated with positive polarity lightning discharges and the charge moment changes of these events were too small to be associated with sprites and were about two orders of magnitude smaller than required by models that assumed that the emission was from high altitude (>30 km) Relativistic Runaway Electron Avalanche (RREA) multiplication. As a result, it is inferred that the TGFs are produced due to massive numbers of runaway electrons being generated within or immediately above thunderstorms.

Currently, nearly all reported TGFs have been detected by satellite-based high-energy photon detectors and it has been found that TGF photons can typically be observed when the space-based detector is located above the source within a cone of ~30° to 40° half angle[10,46]. Largest emitting regions produce the TGF with the most energetic gamma-rays. TGFs have time varying spectra i.e. rapidly varying TGFs are spectrally softer than slowly varying TGFs. Global TGF frequency is >500/day. Recently, it has been observed that TGFs occur during the strengthening phase of the encompassing storm system[94].

Roberts et al[94] studied 37 TGFs originated from tropical storm system (Typhoons Nangka and Bolaven, Hurricanes Paula, Manuel and Julio, Tropical storms Sonia and Emang) and found that they occurred predominantly from the outer rainbands of hurricane and severe tropical cyclones because of the more lightning activity in those regions. The large number of photons ($\sim10^{17}$) with high energy (~20 MeV) in TGFs may undergo photonuclear reactions and produce $\sim10^{12}$ neutrons per TGF[15]. It is found that TGFs are associated with tall tropical thunderstorms with cloud top heights between 13.6 and 17.3 km[103].

These types of thunderstorms are known for strong lightning activity and heavy precipitation. Moreover, TGF producing thunderstorm area spans several orders of magnitude ranging from small isolated thunderstorms (400 km^2) to large mesoscale convective complexes (111,100 km^2). It is found that the source altitudes of the TGFs were between 15 and 21 km[32] and thus it seems that thunderstorm tops might be the source region.

The mean charge moment change associated with TGF producing lightning strokes was found to be 49 C km and all the TGF producing lightning discharges were impulsive (charge transfer within 2 ms) and no evidence of continuing current was found in them[26].

This charge moment change is very small as compared to charge moment change of sprite producing lightning strokes. The sprite producing lightning charge moment change required to generate observable TGFs has been estimated to be around 6000 C km[63].

Source of TGFs located between 21 and 15 km produces 10^{16} to 10^{17} runaway electrons respectively. Such a large number of electrons produce measurable current and charge moment changes. The total charge moment is estimated to be $(2\times 10^{-4}\ C/m)\times R^2$ where R is the radius of the TGF source region. The total peak current from TGF ions (not the lightning) is estimated to be 0.1 kA and 2 kA at altitudes of 21 km and 15 km respectively.

The global TGF frequency was estimated[100] and it was found of the order of 10 min^{-1}. Later, the global TGF production rate within ±38° latitude was found about 35 TGFs per minute[83]. The typical total energy radiated by a TGF is ∼1 kJ[9]. It is observed that the TGFs are produced in a mature phase of the thunderstorm when CG lightning activity becomes high.

Recently, global distribution of the TGFs detected by AGILE and RHESSI for the period from March 2009 to July 2012 has been analysed and on the basis of lower TGF/lightning ratio over America than other regions, it was suggested that meteorological regional differences are important for the TGF production[43].

It is observed that diurnal cycle of TGFs peaks in the afternoon suggests that solar irradiance and consequently Convective Available Potential Energy (CAPE) and convective thunderstorms help to get the right conditions for TGF production[43]. CAPE is a measure of the buoyancy available for convective updrafts. Moreover, they have shown that 75% TGFs detected by AGILE prefer high values of CAPE (>2588 J/kg), lightning stroke rates (>80 strokes/min), number of storms (>9) and coverage area of clouds with temperatures below –70 °C (>26,000 km^2). These conditions in thunderstorms are more typical in tropics which make them favourable regions for the production of TGFs.

Using Monte-Carlo simulations of TGF production mechanisms (Relativistic Runaway Electron Avalanches (RREAs) and production of thermal runaway electrons at the tip of the lightning leader), it is found that TGF events are accompanied with detectable levels of optical emissions[117]. These optical emissions dominate in blue or purplish blue colour. Optical emissions produced during the acceleration of thermal runaway electrons in lightning leader fields are more intense than those associated with RREAs.

Previous research has revealed that TGFs are produced during the initial breakdown stage of intracloud lightning flashes, the first 5-20 ms of a flash. Recently, Albrechtsen et al[3] reported that intrinsically weak TGFs are also produced by less than 1% of IC flashes which can increase the previous reported TGF production rate. Further they reported that these weak TGFs are more likely to produce at higher latitudes places due to their lower altitude of the tropopause (cloud tops) because any TGF produced here will experience more attenuation from the denser atmosphere before reaching the RHESSI instrument.

In addition, they also described that TGFs are more likely to produce over ocean or coast because thunderstorms in these areas are able to develop a higher potential difference before discharging. Fig. 1 shows the time profile of recorded TGFs.

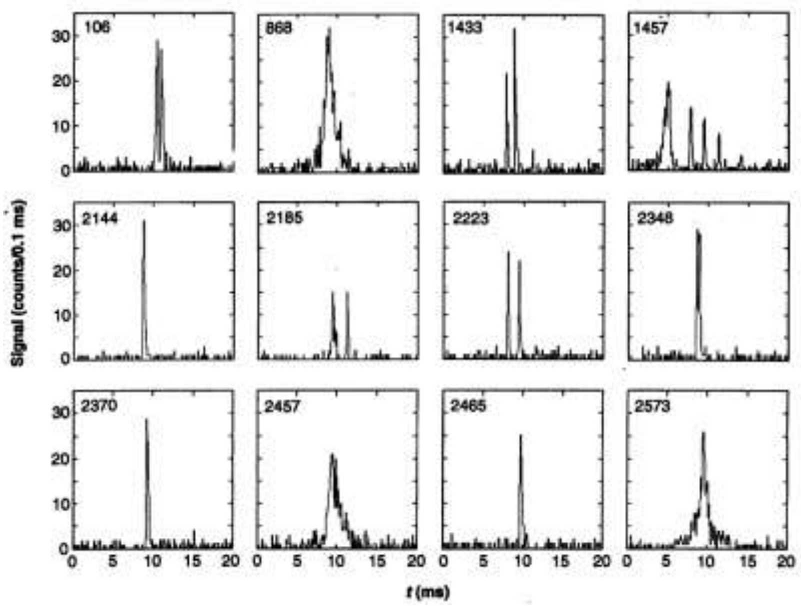

Fig. 1: Time profile of 12 TGFs events recorded between April 1991 and October 1993. Five of the events (106, 1433, 2185, 2223 and 2348) consist of two closely spaced pulses from 1 to 4 milliseconds. Event no 1457 consists of at least 4 distinct pulses of similar shape but variable spacing. Typical rise and fall times are ~0.1 to 0.5 milliseconds[44]

Observations of Terrestrial Gamma-ray Flashes (TGFs)

There are various space borne missions dedicated to high energy astrophysics which detected TGFs. Some of them are given below.

Burst and Transient Source Experiment (BATSE): Burst and Transient Source Experiment (BATSE) was one of the four experiments on board of the Compton Gamma Ray Observatory (CGRO) and it detected the first gamma ray flash from Earth. CGRO was launched in April 1991 by NASA to perform observations of celestial gamma ray sources. CGRO was a low Earth orbiting satellite (~450 km altitude) with inclination of 28.5˚. BATSE consisted of eight Sodium Iodide (NaI) Large Area Detector (LAD), each 2000 cm^2 sensitive to photons with energies from 20 keV to 2 MeV[44].

BATSE was able to detect the only longest and most intense TGFs. The TGF energy spectrum measured by BATSE was harder than energy spectra of Gamma Ray Bursts (GRB). The TGFs measured by BATSE typically contain about 100 counts and have a duration 0.67-10.71 ms[79]. TGFs were observed in single and multiple pulses each lasting ~ 1 ms (Fig. 1). BATSE detected total 78 TGFs during its 9 years lifetime.

However, some of the events which were considered early as TGFs were actually electrons and positron beams with energy more than 30 MeV. These electrons and positrons in the upper atmosphere are produced due to the Compton scattering and pair production of the γ-rays of 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[34].

Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI): RHESSI was the next satellite to report detections of TGFs after BATSE. However, its primary mission was to study solar flares but its instruments were capable to detect TGFs as well. RHESSI was launched on 5th February 2002 to an orbit of ~ 600 km altitude with an inclination of 38˚.

It was the first satellite to accurately measure TGFs. RHESSI continuously collected data, while BATSE had a trigger system which makes it possible to search weak TGFs too. The RHESSI instruments consist of nine Germanium detectors inside an aluminium cryostat. This is able to sense the photons of energy between 25 keV to 17 MeV and telemeters the data to ground[50]. The total effective area of the RHESSI detector is 239 cm^2 for a typical TGF spectrum.

Grefenstette et al[50] presented the first RHESSI TGF catalog in which they reported 820 TGFs detected between March of 2002 and February of 2008. It has been shown that there is no detectable change in the spectrum of TGFs when they are grouped by brightness, geographic latitude, geomagnetic latitude, or the local day or night[50]. Moreover, they found the average rate of occurrence of 160 TGF per year.

Gjesteland et al[47] presented a more sophisticated another search algorithm for identifying the TGFs in the RHESSI data from period 2004-2006 and found more than twice (~350 TGFs/year) as many TGFs previously reported[50]. Later, Østgaard et al[85] using World Wide Lightning Location Network (WWLLN) and RHESSI data identified at least 141 and probably as many as 191 weak TGFs that were not the part of previously detected TGFs supporting TGF production rate is more than previously reported.

RHESSI also detected three TGFs over Mediterranean basin on 27 May 2004, 7 November 2004 and 16 October, 2006 where the occurrence rate of these events is rare. The thunderclouds (cloud top higher than 10-12 km) connected with second and third events were associated with heavy precipitation and intense lightning activity and produced one TGF (second one) among the brightest ever measured by RHESSI. This bright event contained ~3 × 10^{18} initial photons with energy >1 MeV and occurred at altitude of ≤ 12 km. On 25 October 2012, the RHESSI and the Tropical Rainfall Measuring Mission (TRMM) satellites passed over a thunderstorm on the coast of Sri Lanka and observed a TGF associated with a lightning discharge[49].

The causative lightning discharge radiated very low frequency (VLF) radio emissions and the TGF source location was found in the convective core of the cloud but it was not clear that which signal came first: the gamma emission or the optical emission from causative lightning. RHESSI was decommissioned on 16 August 2018 due to communication difficulties after more than 16 years of successful operations.

Astro-rivelatore Gamma a Immagini LEggero (AGILE): AGILE is a satellite operated by the Italian Space Agency. It is designed to observe distant gamma-ray sources. It was launched on 23rd April 2007 from Satish Dhawan Space Centre (India) on a PSLV rocket and put in an equatorial orbit with an inclination angle of 2.47˚ and an average altitude of 535 km[105]. The AGILE scientific payload is made of three detectors: a Gamma-Ray Imaging Detector (GRID) (sensitive in the energy range ~30 MeV-50 GeV), a hard X-ray imager (sensitive in the range18-60 keV) and a Mini-Calorimeter (sensitive in the range 350 keV-100 MeV). A plastic anticoincidence shield surrounds the payload. The detector detecting most TGFs is the Mini-Calorimeter (MCAL). Like BATSE, MCAL is triggered. In 6 years of activity, from 1 March 2009 to 22 March 2015, the AGILE satellite detected a total of 498 TGFs.

At the end of March 2015, the onboard software configuration of the AGILE satellite was modified in order to disable the veto signal of the anticoincidence shield for the mini-calorimeter instrument[74]. The configuration change was highly successful resulting in an increase of one order of magnitude in TGF detection rate. With the enhanced configuration, from 23 March 2015 to 13 March 2016, with a lack of data for the month of September due to technical issues, the AGILE satellite detected a total of 648 TGFs[111].

This represents the highest detection rate (TGF/km^2/year) to date for any satellite. The AGILE quasi-equatorial orbit has the smallest inclination (2.47°) ever achieved by a high-energy astrophysics mission which puts the satellite in a privileged position to detect more TGFs coming from the same thunderstorm. The AGILE satellite clearly established the multiple occurrences of TGFs from convective thunderstorms, both on timescales of minutes to several hours[111].

Fermi Gamma-ray Space Telescope (FGST)

The Fermi Gamma-ray Space Telescope is a satellite launched on 11th June 2008 with an inclination of 25.6˚ and an altitude of 565 km which causes it to spend long times over areas in the tropics where thunderstorms and TGFs are common[9]. It consists of two instruments designed to observe gamma rays; the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). The LAT is a pair-conversion telescope designed to cover the energy range from 20 MeV to more than 300 GeV[4]. The GBM consists of 12 NaI scintillators detectors to cover an energy range of ~8 keV to ~1 MeV and two Bismuth Germanate Oxide (BGO) to cover an energy range of ~200 keV to ~40 MeV. Like BATSE, but unlike RHESSI, GBM TGF data are also obtained by a "triggering" process but with a 16 ms trigger time instead of BATSE's 64 ms. During the first year of observation, Fermi detected 12 TGFs[9].

Most of the TGFs were found with typical maximum energy of ~30 MeV, with one TGF having a ~38 MeV photon, but two of the TGFs are distinctive, being both much longer and softer than the others. Roberts et al[95] presented the first Fermi Space Telescope Gamma Ray Burst Monitor (GBM) catalog of 4,144 TGFs, detected between 11 July 2008 and 31 July 2016.

Airborne Detector for Energetic Lightning Emissions (ADELE): The ADELE is an array of six gamma ray detectors designed to study the TGF phenomenon at close range. ADELE detected two events of TGFs. The first TGF was detected when it was flying aboard a Gulfstream V jet near two active thunderstorm cells on 21 August 2009 over coastal estuaries on the southeast coast of Georgia near the town Brunswick[101].

During its total flight of ~10 km, it passed from 1213 individual lightning flashes. The duration of the TGF was observed slightly less than 1 ms with significant spectral content above 1 MeV. This event was found to be associated with long duration, complex +IC lightning flash. The lightning flash associated sferics extended over 54 ms and included several ultralow frequency (ULF) pulses corresponding to charge moment changes of up to 30 C km. The second TGF was detected by ADELE aboard the National Oceanic and Atmospheric Administration's Hurricane Hunter WP-3D Orion during reconnaissance in eyewall of Hurricane Patricia on Oct 28, 2015[8].

ADELE measured 184 counts of ionizing radiation within 150 μs, coincident with the detection of a nearby lightning flash. The radio signal from the nearby lightning flash inferred that this was a typical TGF, with a beam of RREA moving upwards. In addition, they also reported the beam of positrons, the antimatter counterpart of electrons blasted towards the ground. Besides the above mentioned two TGFs, ADELE also detected 12 gamma ray glows during the 2009 campaign.

Relativistic ELECtrons (RELEC) Mission

The relativistic electrons (RELEC) experiment on board satellite Vernov was launched on July 08, 2014 with an inclination of 98.4° to study magnetospheric relativistic electron precipitation and its possible influence on the upper atmosphere as well as the observation of Transient Luminous Events (TLE) and Terrestrial Gamma Flashes (TGF) across a broad range of the electromagnetic spectrum[86]. The onboard instruments include the DRGE (DRGE1, DRGE2 and DRGE3), DUV, MTEL (Telescope-T), low frequency analyzer (LFA or NChA), radio frequency analyzer (RFA or RChA) and electronic unit (BE).

The DRGE1 and DRGE2 were the main instruments for TGF observation with energy range of 0.01-3.0 MeV. During the observation period from July 20 to December 10, 2014, five TGF candidates were found. The TGF detection rate was about 15 events per month. The most intensive flash was detected in the western part of the Pacific Ocean in the vicinity of active thunderstorm regions.

Atmospheric Space Interactions Monitor (ASIM)

Most recently, the observatory Atmospheric Space Interactions Monitor (ASIM) a mission of European Space Agency (ESA) was sent to International Space Station (ISS) on 2 April 2018. This is designed mainly to uncover the invisible process that derives the thunderstorms, lightning, upper atmospheric lightning (red sprites, blue jets, gigantic jets and elves) and TGFs.

In addition, it will also observe chemical effects on the atmosphere, cloud properties, aerosol loading and other processes and parameters relevant to climate. ISS offers ASIM the perfect platform to observe the Earth because it flies relatively close to the Earth at 370-460 km altitude with an inclination of 51.6° and often travels over regions of major active thunderstorms[80].

ASIM is designed with very sensitive instruments in order to detect the TGFs and gigantic lightning above the thunderclouds. In addition, ASIM detector has the capability to determine the direction of arrival of the flash photons, allowing us to pinpoint their source location[80].

Recently, Marisaldi et al[75] reported the observations of two TGFs detected simultaneously by Fermi and ASIM on 21 June 2018 and 5 September 2018. They found that ASIM is detecting about an order of magnitude larger number of photons than Fermi, allowing a much more detailed analysis. It has detected over 200 terrestrial gamma-ray flashes and, for nearly 30 of them, have pinpointed their location of origin since its starting of operation[42].

Most recently, Neubert et al[81] using ASIM observed a TGF and an associated Elve i.e. TGF and Elve were powered by the same lightning stroke. The TGF occurred at the onset of a lightning current pulse that generated the Elve in the early stage of the lightning flash.

Some other projects like Tool for the Analysis of RAdiations from lightNIngs and Sprites (TARANIS), Terrestrial RaY Analysis and Detection (TRYAD) and Universat-SOCRAT the space missions of French Space Agency (CNES), University of Alabama in Huntsville (UAH) and Lomonosov Moscow State University (MSU) respectively will also be launched in near future to understand much more about the lightning discharges, transient luminous events and TGFs.

Possible Production Mechanisms of TGFs

Although the physics behind the TGFs production is under debate even after more than 20 years of their experimental and theoretical research, several theories have been developed. A concrete theory which can describe all the features of TGFs simultaneously still has not been developed. TGFs are thought to be generated by bremsstrahlung emissions from an avalanche of energetic electrons. The source of the accelerating electric field which makes the ambient electrons energetic remains a topic of speculation.

The possible candidates included electric field resulting from charge separation within a thundercloud, the quasi-static electric field after a lightning discharge or the potent but ephemeral fields in lightning streamers and leaders. There are evidences that lightning discharge is followed by TGFs[9,23] and also TGFs occur prior to the lightning discharge[9,24,81] so there may be multiple physical mechanisms responsible for the generation of TGFs. The proposed popular theories which have been given since their first observation are discussed below.

TGFs Produced by Lightning Generated Electro-Magnetic Pulses (EMPs): An electromagnetic pulse (EMP) is a short burst of electromagnetic energy delivered by huge lightning current. When TGFs were first discovered, they were considered to be a rare phenomenon. The BATSE detected only 78 TGFs in 9 years[79].

Inan and Lehtinen[56] suggested that TGFs could be produced in the electrical fields from the electromagnetic pulses (EMPs) emitted by rapidly moving lightning return stroke. Later, analysis of ELF/VLF broadband data from Palmer station, Antarctica indicated that majority of TGF events (76%) are associated with lightning discharges and the peak VLF intensity of the TGF associated lightning discharges is found among the most intense in the same storm[57]. Since the peak VLF power of a radio atmospheric is directly proportional to the intensity of lightning,[92] therefore TGFs should be produced by EMPs generated by intense lightning. The electric field of EMPs radiated by return stroke propagating upwards with velocity v_r and current I is given by Krider:[60]

$$E(t) = \frac{\mu_0 I(t - R/c)}{2\pi R} \frac{c\beta \sin\theta}{1 - \beta^2 \cos^2\theta} \quad (1)$$

where R is the distance from the source; θ is the zenith angle and $\beta = v_r / c$, assuming that the EMP is radiated very close to the surface of earth and *c* indicates velocity of light in free space.

Highly energetic seed electrons from cosmic rays in the ambient atmosphere in the presence of aforementioned electric field given in eq. 1 produce relativistic runaway electron avalanche and produce TGF via Bremsstrahlung emission. However, this model implies very high return stroke currents with peak values (>450−700 kA) and fast return strokes (0.99*c*-0.99*c*, *c* is speed of light). Such types of lightning are rare and they concluded that EMP fields could produce 6-12 TGFs per day which is less than the estimate of ~50 TGFs per day by Smith et al.[98] More recently, based on the number of TGFs measured by Fermi GBM the estimate of global production rate varies from 1100 TGFs/day[11] to 1200 TGFs/day[108]. Nevertheless, some of the TGFs may be produced by EMPs from rapidly moving return strokes[23].

Relativistic Runaway Electron Avalanche (RREA) Mechanism and Quasi-Electrostatic Field Theory: Nobel award winner Sir C. T. R. Wilson predicted in 1925 on the basis of observations of the tracks of energetic electrons in his cloud chamber that electrons accelerated in high electric fields in thunderstorms would emit high energy radiation[116]. However, the possibility of their avalanche was not considered. Some researchers developed the runaway electron model to explain the electron acceleration in the thundercloud electric fields[51,52].

According to them, when the electron is passed through any medium, it experiences a braking force due to friction and collision with the medium constituents. However, if such electron has enough energy and it is placed in a strong enough electric field, then it would gain more energy from the field than it loses in collisions; such electron is called “relativistic runaway” electron which collides with other molecules and produces more relativistic runaway electrons. One more important parameter is spatial scale of electric field that must be large enough as compared to characteristic length (l_a) required for the exponential growth of relativistic runaway electron avalanche (RREA). For example, in air at atmospheric pressure, l_a is found equal to ~50 m[52].

All these conditions i.e. strong electric field, energetic electrons and large spatial scale of electric field existed in the atmosphere of thunderstorms. Before any lightning discharge, charges are continuously accumulated within the thundercloud. The top and bottom of the thundercloud become positively and negatively charged respectively as shown in the fig. 2. The separation of opposite nature of charges produced strong electric field within the thundercloud called thundercloud electric field E_{Th} of the order of 100 kV/m. Same order of electric field can also be created between the lower negative charge centre of the thundercloud to the ground. Marshall et al[76] observed the value of E_{Th} in the thunderclouds ~186 kV/m at an altitude of 5.77 km, which is equivalent to 370 kV/m for runaway electrons at sea level.

However, the threshold value of electric field (E_t) required for RREA at sea level is 216 kV/m and decreases exponentially with altitude[52]. The characteristic size of thunderstorms (order of 1000 m) is much larger than characteristic length needed for relativistic runaway electrons avalanche (RREA). Now, RREA mechanism requires the seed particles (electrons) of high energy (typically 0.1-1 MeV). Such energetic electrons come from the extensive air shower (EAS) generated by high-energy cosmic rays in ambient air.

Recently, Lindy et al[65] using computer simulation reported the cosmic-ray secondary electron distribution and energy spectrum at thunderstorm altitudes and found that the average secondary electron energy is > 10 MeV with ∼10% of secondary electrons having energy >100 MeV at thunderstorm altitudes. As the seed particles (cosmic ray electrons) accelerate in strong E_{Th}, they gain more and more energy and eventually become runaway. They collide with atoms in the ambient atmosphere and knock out the secondary electrons. If the secondary electrons also have high enough energy to run away, they too accelerate to high energies and produce further secondary electrons etc.

As such, the total number of energetic electrons grows exponentially in an avalanche. These runaway electrons produce TGFs via bremsstrahlung emission. In the bremsstrahlung process, a high speed electron traveling in a material is scattered by the forces of any atom it encounters. As a high speed electron approaches an atom, it will interact with the electric field of positive nucleus of the atom and it will be scattered from its original path. The scattered electron will exit the material with less energy. According to conservation of energy, the loss of energy by the electron due to scattering must be produced in some other forms and that is a gamma-ray photon. Again when the gamma-ray photon interact with the another atmospheric atom (Nitrogen or Oxygen), a secondary electron is produced along with an antimatter particle called positron via pair production.

The TGF energy spectrum as measured by RHESSI was found consistent with “Bremsstrahlung emission” from relativistic runaway electrons generated by RREA. In addition, the presence of photoneutrons in TGFs indicates the existence of ≥10 MeV photons, clearly shows a strong proxy for the presence of energetic electrons and RREA[16]. Runaway process is one of the strong candidates for the production of high altitude discharges like red sprites and blue jets above thunderstorms.

However, researchers did not find any direct link between TGFs and high altitude discharges. Dwyer and Smith[32] compared their calculated spectra of TGFs using Monte-Carlo simulations of runaway breakdown with the averaged photon spectra observed from RHESSI and BATSE and found that majority of the TGFs should be generated at altitudes of 15-21 km. These lower altitudes are consistent with the inside region and tops of tropical thunderstorms. Further, it is reported that TGFs are linked to the electrical activity in atmospheric regions in or above thunderstorms[44,99].

In the same way, the quasi electrostatic (QE) field E generated by +CG lightning discharge extending from cloud tops to the lower ionosphere accelerates the ambient energetic electrons to runaway electrons. The mechanism of production of QE field is illustrated in fig. 2 (after +CG lightning) and was provided by several researchers[6,89]. The first direct experimental evidence of TGF production by RREA in QE field generated by +CG lightning was reported by Inan et al.[55]

They observed that the sferics associated with +CG lightning occurred 1.4±1 ms earlier than the peak of γ-ray burst (TGF of energy more than 1 MeV) which indicates that the QE field which immediately follow the +CG lightning accelerating the energetic electrons and produce TGFs via bremsstrahlung emission.

Later, Lehtinen et al[62] applied Monte Carlo simulation to the high energy (20 keV-10 MeV) runaway electrons due to QE field in the middle atmosphere and calculated gamma ray flux of the same order as the TGFs observed by the Burst and Transient Source Experiment.

A thundercloud consists of two layers of positive and negative charges. During the thundercloud charging before lightning discharge, a space charge layer is induced above the positive charge layer of thundercloud due to the finite conductivity gradient of the atmosphere which shields the higher altitudes from QE fields of thundercloud charges as shown in fig. 2. After quickly removal of positive charge layer by a +CG lightning, a vertical QE field E is established in the atmosphere at all altitudes above the thundercloud due to the remaining charges of opposite sign in and above the thundercloud. This field endures for a time equal to the local relaxation time $\tau_r = \varepsilon_0 / \sigma$, where ε_0 is the permittivity of vacuum and σ is the local ionospheric conductivity in the presence of the electric field. The quasi-electrostatic field E is given by Raizer et al:[91]

$$E = \frac{zQ}{\pi\varepsilon_0 h^3}\left[1+\left(\frac{h}{2h_i - h}\right)^3\right] \tag{2}$$

where Q is the charge left in the thundercloud after positive CG lightning; z is the height of charge Q; h_i is the height of the ionosphere and h is altitude.

The relaxation time (τ_r) of QE filed E is tens of ms. During this time, seed electrons (cosmic ray electrons) are accelerated upwards, collide with the air particles, produce avalanche of runaway electrons and generate TGFs via Bremsstrahlung emission. Most of the experimental observations show that TGFs are produced inside the thunderclouds or just adjacent to their top i.e. at altitudes of 10-20 km. However, Østgaard et al[82] reported that a significant portion of TGFs is produced at higher altitudes (30-40 km). This may be due to the QE field $\boldsymbol{E}$. In these mechanisms we did not introduce the effect of positrons which are created during pair production.

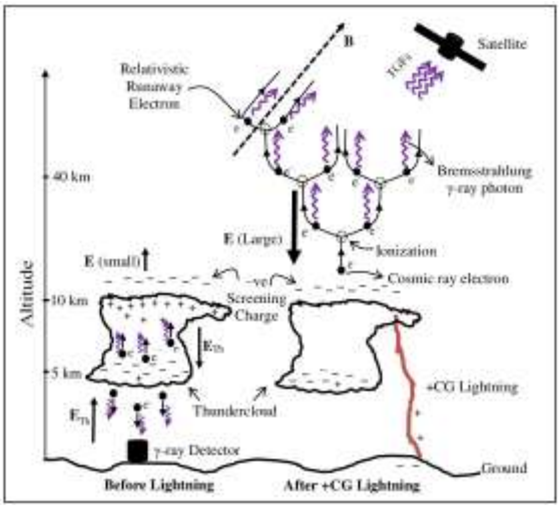

Fig. 2: Depiction of RREA mechanism. The diagram shows how the RREA produces TGFs before and after the lightning. TGFs may be produced within the thundercloud region or below the negative charge centre to the ground region. Right side of the diagram shows the condition after +CG lightning. The formation of quasi-electrostatic field (*E*) above the top of the thundercloud produces RREA and generates TGFs. At lower altitudes, the electrons move along electric field and at higher altitudes they move along geomagnetic field *B*

Relativistic Feedback Discharge (RFD) Mechanism: This is one of the most viable TGF production mechanisms in which the effect of positrons has been introduced. Although, the classical RREA mechanism discussed above produces large amount of runaway electrons, it is not enough to produce detectable TGFs. There is a requirement of $\sim 10^{17}$ electrons to produce a detectable TGF in space[32]. According to RREA model by taking threshold electric field $E_t = 3\times10^5$V/m at STP (larger than RREA threshold) and total available potential ~100 MV (maximum value found in thunderstorms), the number of runaway electrons was calculated around $<10^6$ only[48].

However, for electric fields close to the conventional breakdown threshold (3×10^6 V/m at STP) and total potential of 400 MV, the number of runaway electrons comes out to be $> 10^{21}$ but there are lack of measurements that supports that one can have such large electric fields and potentials inside the thunder clouds[48].

Therefore, one should seek another model or above stated runaway breakdown model must be modified. Dwyer[30,33,35] introduced a new mechanism called relativistic feedback discharge (RFD) mechanism to produce a very large number of electrons required to produce TGFs. This mechanism involves the positive feedback effects from positrons and energetic photons. According to this mechanism, when an electron having sufficient energy (0.1-1 MeV) accelerates in the presence of thundercloud electric field, it becomes runaway. This runaway electron interacts with air molecules and produces other electrons. Those electrons which have sufficient energy will also become runaway and produce more and more free electrons.

In this way, primary avalanches of runaway electrons are produced. These avalanches of runaway electrons emit Bremsstrahlung X-rays/γ-rays that may either Compton backscatter or pair produces in air. If the backscattered photons propagate to the start of the primary avalanche region and produce other runaway electrons, either via Compton scattering or photoelectric effect, then a secondary avalanche is created.

Alternatively, the positrons created by pair production propagate in the ambient thundercloud electric field and run away in the opposite direction of the electrons. This has been confirmed experimentally that the positrons propagate in the opposite direction of electron during TGF production[8]. The positrons are relativistic and travel a significant distance (in kilometres) before annihilating.

If these positrons propagate to the start of the primary avalanche region, they can produce additional runaway electrons via hard elastic scattering with atomic electrons in the air (i.e. Bhaba scattering), thereby producing secondary avalanches. These secondary avalanches can in turn emit more X-rays/γ-rays that Compton scatter or pair produces, resulting in more feedback and more avalanches.

In addition, second-order feedback effects can occur such as feedback from Bremsstrahlung X-rays emitted from the backward propagating positrons and feedback from the 511 keV gamma rays emitted by the annihilating positrons.

As a result of this positive feedback, the number of runaway electron avalanches increases exponentially on a time scale measured in microseconds. These exponential increases of runaway electrons produce TGFs via Bremsstrahlung emission. Using detailed Monte Carlo calculations, it is found that once relativistic feedback fully commences, electrical breakdown will occur and the ambient electric field, extending over cubic kilometers, will be discharged in as little as 20 μs.

Furthermore, the flux of energetic electrons and X-rays generated by this mechanism can exceed the flux generated by the classical RREAs model by a factor of 10^{13}, making relativistic feedback discharge a good candidate for explaining terrestrial gamma-ray flashes and other high-energy phenomena observed in the Earth's atmosphere[33].

It should be noted that RFD is also a high current electric discharge just like normal lightning with length scale measured in kilometres and hence it generates the current pulses that generate radio emissions. However, RFD involves little visible light as compared to normal lightning, therefore it may be viewed as a dark lightning[38].

In the above discussion, we have seen the effect of positrons created by pair production due to the interaction of γ-rays and atmospheric nuclei. Recently, using Monte-Carlo simulations it is described that direct electron-positron pair production may occur from the interaction of energetic runaway electrons with atomic nuclei without requiring the γ-rays as mediators[112]. This process is also known as "trident process". The positrons produced in this process contribute to relativistic feedback and become especially important when the feedback factor (the ratio of the next generation runaway electrons number to the current runaway electrons number) value approaches unity. In this way, steady state flux of runaway electrons increases significantly.

In addition, when the electrostatic field forms in a narrow area, the trident process dominates in relativistic feedback. Trident process acts as an additional source of positrons for positron Bremsstrahlung and positron annihilation processes. In this way it increases the intensity of TGFs.

TGF Production by Lightning Current Pulses (Cold Runaway Electron Model): The TGF spectrum involves photons energy up to more than 100 MeV[106]. In fig. 3, the Monte Carlo simulation results strongly suggest that the TGF photons of energy more than 30 MeV cannot be produced by classical RREA mechanism developed in large scale weak homogeneous thundercloud electric field[17], it may be produced by runaway electrons strongly accelerated in highly inhomogeneous fields around the tip of the stepping lightning leader. However, the relation of these electrons to the formation and propagation of stepped leader is still not fully understood. Lightning leaders naturally provide the energetic seed electrons by cold runaway and strong electric fields by charge accumulation on the lightning leader channel[16].

The first experimental evidence of association of TGFs with lightning discharges by measuring ELF/VLF radio atmospherics was provided by Inan et al.[55] Most recently, it was observed that the TGF occurred at the onset of a lightning current pulse followed by Elves. TGFs are typically observed in close time coincidence with lightning discharge detectable in radio signals[23].

Inan et al[57] analysed ELF/VLF broad band data from Palmer Station, Antarctica and reported that 76% of the TGF detected on RHESSI spacecraft were associated with cloud-to-ground lightning. Stanley et al[104] observed atmospheric electric field change (sferic) waveforms and found that they were associated with the TGFs. According to them, five TGF associated sferic waveforms were found to be consistent with a positive-polarity intra-cloud (+IC) discharge process (initial breakdown pulses) which transported electrons upwards from negative charge centre to the positive charge centre of the thundercloud. Carlson et al[16] using computer simulations described that the TGFs are produced by active lightning leader channels.

Lu et al[68] reported the observation with the North Alabama Lightning Mapping Array related to a terrestrial gamma-ray flash (TGF) detected by RHESSI on 26 July 2008 and suggested that the leader development might be involved in the TGF production. The first clear picture of the intracloud lightning processes that occur before, during and after TGF production was provided by Cummer et al.[28] They found that most of the TGFs were produced several milliseconds after the leader had initiated and reached 1-2 km in length. TGF associated lightning leaders are found relatively long, relatively fast ($0.8\text{-}1.0\times10^6$ m/s) and possibly accelerating with altitude[28].

More recently, the bursts of gamma ray showers have been observed in coincidence with downward propagating negative leaders in lightning flashes by the Telescope Array Surface Detector (TASD)[2].

The showers arrived in a sequence of 2-5 short-duration ($\leq 10\,\mu$s) bursts over time intervals of several hundred microseconds and originated at an altitude of $\simeq$3-5 km above ground level during the first 1-2 ms of downward negative leader breakdown at the beginning of cloud-to-ground lightning flashes.

The showers primarily consisted of downward-beamed γ-radiation. The peak currents in TGF associated lightning are often found very large (>100 kA). All these observations suggest that TGFs are also somehow associated with the lightning leaders.

Carlson et al[14] proposed a mechanism for TGF production by current pulses in lightning leader channels. They first surveyed the requirements on TGF production and found the 15-20 km production altitude, 10^{17} energetic electrons, lightning electric fields that exceed the RREA threshold but less than the conventional breakdown threshold and at least 20 MV total available potential. They described that the TGFs may be produced by electric fields near leaders and leader steps. If TGFs are emitted on a time scale of 0.5 milliseconds, the process that produces them must produce a population of energetic electrons on such a time scale.

As we know that there are various processes which take place to initiate the lightning discharge and their time scales are different. One of the lightning processes “current pulses along the lightning channel: return strokes, K changes and M components” has the best suited time comparable to the TGF production time. Dwyer et al[31] observed an intense gamma-ray burst (energy of gamma rays extending more than 10 MeV) on ground in association with the strong current pulse of 11 kA during rocket triggered lightning. During the propagation of current pulses, the charge is redistributed which enhances the electric field at the tip of the leader or around the leader channel as shown in fig. 4.

Modeling results have indicated that the electric field at the tip of streamers associated to the leader (E_{tip}) can reach values of $\sim$10 E_k where E_k=32 kV/m is the conventional breakdown threshold electric field at the sea level[90]. The enhanced electric field near the leader channel ionizes the atmospheric atoms/molecules and produces large number of electrons of energy >0.1 MeV. Such electrons have sufficient high energy to serve as seed electrons for RREA.

Moss et al[78] estimated the seed flux using detailed Monte Carlo simulations by an active leader tip of the order of 10^{18} s^{-1} i.e. 10^{12} seed electrons produced in ~ 1 µs. These electrons are emitted in a region where the available voltage (~100 MV) in thundercloud can accelerate them to high energy and ambient electric field in streamer zone of leader can result in RREA multiplication of the number of energetic particles.

In this process, there is no requirement of seed electrons. This process may produce the required number of energetic electrons (~10^{17}). This population of energetic electrons then produces TGFs via bremsstrahlung.

This mechanism requires large current pulses through high altitude leader channel to produce observable TGFs because at low altitudes the atmospheric density and frictional losses will be more which may suppress the RREA growth rate, consequently low altitude leaders would be less likely to produce intense TGFs. Since this mechanism does not require extreme values of lightning parameters, so it is inferred that energetic photon emissions (TGFs) accompany lightning leaders. It is noted that any TGF observed without a lightning discharge or closely associated current pulse must be due to another mechanism.

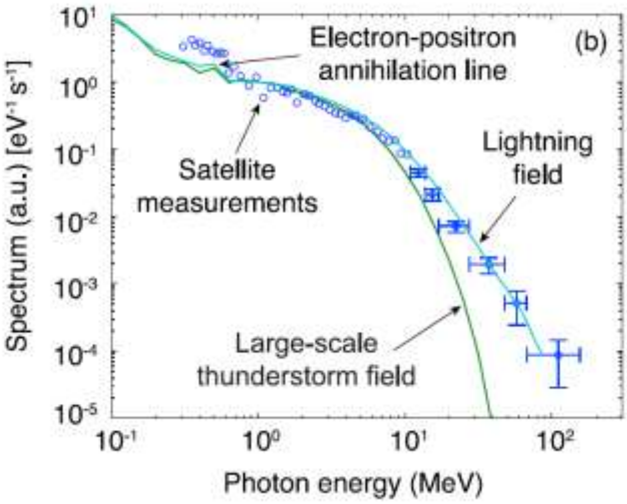

Fig. 3: Circles with error bars is observed as TGF spectrum at satellite altitudes. The spectrum produced by RREA process is shown by green line. Blue line represents the TGF spectrum by the mechanism of acceleration of thermal electrons due to the inhomogeneous electric field around the tip of lightning leader confirming the association of TGFs with cold runaway mechanism[17]

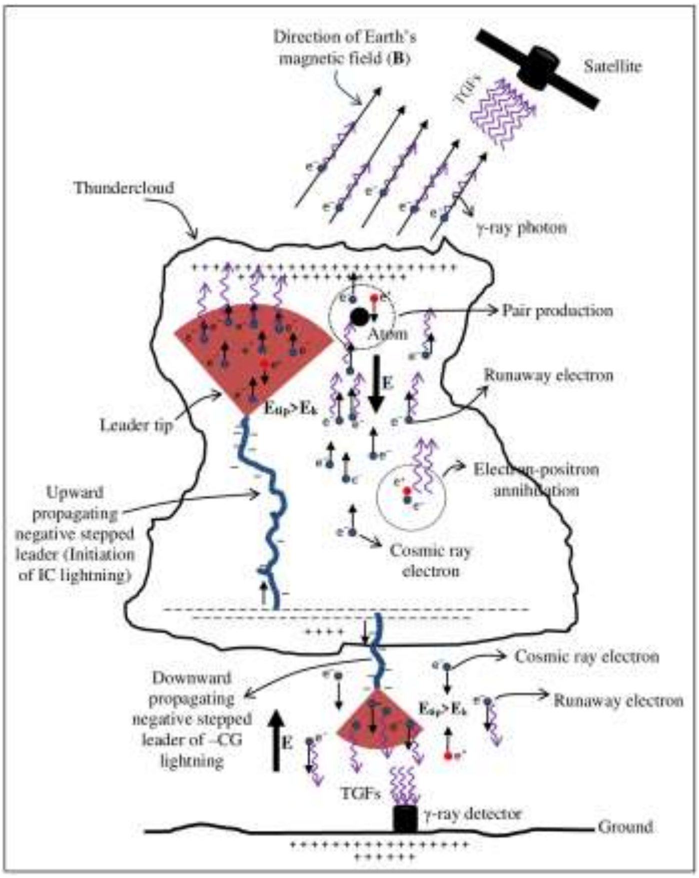

Fig. 4: Schematic diagram shows the different mechanisms i.e. runaway breakdown, relativistic feedback discharge and lightning current pulses for the TGF production. The upper and lower dotted circle represent the "pair production" and "pair annihilation" processes respectively. In each mechanisms, when electron travels in the ambient electric field it gains enough energy and emit γ-radiation via "bremsstrahlung process". The electrons and positrons move in the opposite and in the direction of ambient electric field respectively. The symbols E_{tip}, E_k and E represent the electric fields at the tip of the leader, conventional breakdown electric field of air and thundercloud electric field respectively

Gamma-Ray Glow or Thunderstorm Ground Enhancements (TGEs)

Like TGFs, another phenomenon observed mostly near the tops of thunderstorms and sometime on Earth beneath thunderclouds is called as "gamma ray glow" or thunderstorm ground enhancements (TGE)[18]. TGE includes enhanced flux of γ-rays, electrons and neutrons. The neutrons are released by photonuclear reactions when the gamma rays hit the atomic nuclei of air molecules. Gamma ray glows are fundamentally distinct from TGFs, since gamma ray glows occur on time scales of seconds to tens of minutes, while TGFs occur on time scales of tens to hundreds of microseconds. They also differ in brightness and timing with regard to lightning discharge. Parks et al[88] observed the gamma ray glows in the form of X-rays of high energy (3 to >12 keV) with the aid of a detector mounted onboard a jet flying through the thunderstorms. Later, McCarthy and Parks[77] detected the same high energy (5 to >112 keV) X-ray of duration several seconds using an X-ray detector flown into thunderstorms. They described that these energetic radiation were produced by the thunderstorm static electric field and support the lightning discharge activity.

Tsuchiya et al[110] reported the first observation of 3-30 MeV prolonged (less than 3 minutes) gamma ray emission during winter thunderstorm on December 30, 2010 in a coastal area along the sea of Japan. The gamma ray flux was abruptly terminated less than 800 ms before the lightning discharge that occurred over 5 km away from the experimental site. Eack et al[40] observed long duration (90 sec) X-ray emission in thunderstorms using a series of four balloon flights with an X-ray spectrometer and an electric field meter. They described that these energetic radiation were generated by RREA mechanism in the thundercloud and cease after lightning discharge.

Recently, two gamma ray glows were detected over Northern Australia region at 12 km altitude with durations of 20 and 30 s with the In-Flight Lightning Damage Assessment System (ILDAS) installed onboard at airbus A340 aircraft[59]. The first glow of life time 20 s was terminated by a nearby lightning possibly due to a rapid discharging of the thundercloud electric field. Most recently, another gamma ray glow of energy extended up to 20 MeV, lasted for 75 ms and then abruptly terminated with a nearby lightning discharge observed in Japan[113].

However, they described that lightning discharge was not triggered by the glow because the lightning discharge was started ~15 km away from the gamma ray observation site. The spectrum of gamma ray glows is found similar to the TGFs but is orders of magnitude less bright[5]. Gamma ray glows play an important role in the overall charge balance of thunderstorms[58]. It has been observed that two types of lightning discharges namely –CG and normal-polarity ICs (+IC) terminate TGE via reducing the main negative charge i.e. upward directed electric field, accelerating electrons toward ground in the thunderclouds[21].

Chilingarian et al[22] presented the first catalog of more than 100 TGE observed on Mountain Aragats, Armenia in 2017. They presented a model of TGE initiation[19]. Thunderclouds are electrically charged and show typical tripolar charge structure where a main positive charge region exists at the top and main negative charge region at the bottom and a small amount of transient positive charge just below the main negative charge region which is called lower positive charge region (LPCR). According to the latest observation, the main positive charge region is present typically at 10 to ~15 km, the main negative charge region is found between 6 and 9 km and the LPCR between 4 and 6 km altitude[67]. The size of LPCR is much smaller than the main negative charge region. A portion of main negative charge region (equal and opposite of LPCR) and the LPCR at the bottom of cloud form a lower dipole and create the upward directed electric field. In other words, the main negative charge and its image charge in the ground constitute the upward directed electric field and LPCR enhances this electric field[21].

The upward directed electric field transfers the energy to the ambient cosmic ray high energy electrons and accelerates them downward which create relativistic runaway electron avalanche (RREA) and produce TGE. TGE amplitude is proportional to the absolute electric field strength. Radon and its daughter isotopes present in the clouds due to diffusion process may enhance the life time of TGE significantly through emitting radiation of energy <3 MeV[22].

Only when LPCR reduces, then the stepped leader is initiated and propagates towards the ground and classical –CG lightning occurs. The discharge usually occurs just after the maximum particle flux i.e. TGEs are switched off by lightning discharge. A detailed observation and analysis of various TGE events along with near surface electric field and relative humidity concluded that RREA is the only TGE production mechanism[20].

TGF Afterglow

One more important phenomenon related to TGFs also has been observed which lasts from milliseconds to seconds i.e. longer than the microsecond fast TGFs but faster than the seconds to minutes long gamma ray glow or TGE. That is known as TGF afterglow. TGF afterglows are created by TGFs which are triggered by leader propagation and related to fast electric field changes. TGF Afterglows were observed by Gurevich et al[53] in 2011 during a thunderstorm at Tien-Shan Mountain Cosmic Ray Station in the form of long duration (100-600 ms) gamma ray bursts. The TGF afterglow gamma radiation are generated at the all stages of an atmospheric discharge[53].

Recently, Wada et al[114] also detected two TGF afterglows of duration ~200 ms and exhibited a steep rise and decay with time constants of 52.0 ± 4.9 and 59.2 ± 1.7 ms. TGF afterglows are found to initiate at the same time as the glow terminates and lightning discharge takes place[114]. In addition, they recorded a faint annihilation emission at 0.511 MeV for 10 s after the TGF afterglow.

According to Rutjes et al[96], when energetic photons of TGF hit the air molecules (N_2 and O_2), then fast neutrons are released via photonuclear reactions $^{14}N+\gamma \rightarrow {}^{13}N+n$ and $^{16}O+\gamma \rightarrow {}^{15}O+n$. The number of neutrons produced by a typical TGF varies from 10^{12} to 10^{15}. The released neutrons have energy of ten of MeV and so they cool down slowly through collisions with nuclei of air molecules. During thermalization they are captured again by atmospheric nuclei with the release of a high-energy photons via nuclear reactions $^{14}N+n \rightarrow {}^{15}N+\gamma$ and $^{16}O+n \rightarrow {}^{17}O+\gamma$. The released high energy photons constitute TGF afterglow[41].

Further, the nitrogen (^{13}N) atom and oxygen (^{15}O) atoms lose their neutrons and become unstable. They break down and release positrons in the ambient atmosphere via β^+ decay, $^{13}N \rightarrow {}^{13}C+e^+ +\nu_e$ (half-life, 598 s) and $^{15}O \rightarrow {}^{15}N+e^+ +\nu_e$ (half-life, 122 s) where e^+ denotes a positron and ν_e an electron neutrino. Released positrons after travelling a few meters and electrons which are already present in the atmosphere meet and annihilate each other and produce extended gamma ray bursts or delayed emission of energy 0.511 MeV which last for several minutes[41].

The life time, $T_{afterglow}$ of TGF afterglow is altitude (h) dependent and given by Rutjes et al:[96]

$$T_{afterglow} = 0.063\exp\left(\frac{h}{7\ \text{km}}\right)\ \text{s} \tag{3}$$

Further, the region of afterglow occurrence is air density dependent too; less is the air density, more will be the time taken by neutrons to cool down. Hence, the TGF afterglow is much more extended in space and duration at higher altitudes. The TGF afterglow photons are fairly isotropic in contrast to the photons of TGFs and TGE which are highly beamed.

Discussion

TGFs, TGEs and TGF afterglows are the high energy atmospheric phenomena occurring naturally in the Earth's atmosphere. They may impact on atmospheric electrodynamics significantly. The severity of impact depends on their rate of production. Although all these phenomena are originated by RREAs in strong thundercloud/lightning electric field, the connection among them is not well understood. Researchers found a limited observation of their simultaneous occurrence. Recently, Wada et al[114] reported unequivocal simultaneous detection of a gamma-ray glow (~100 s long) termination and a downward TGF, observed from the ground during a winter thunderstorm in Japan on 9 January, 2018. They described that the highly electrified region produced by gamma ray glow acted as the source of seed electrons for RREAs to initiate the TGF.

However, they could not determine whether the glow termination or the downward TGF occurred first. A strong theory which can connect them is required. More than 2700 TGFs have been detected till now in the 10 keV-40 MeV energy range and the average detecting frequency is 1 burst in ~4 days[11,95].

TGFs are just a rare exotic phenomenon or they are part of each and every lightning discharge is hard to predict. All measurements of TGFs so far have been limited by the dynamic range and sensitivity of space borne instruments. Additionally, once TGF γ-ray photons are produced, they attenuate rapidly during the propagation in the atmosphere.

So it is suggested that there may also exist a large population of TGFs which are too weak to be observed by current instruments, either because they are farther away or they are produced at lower altitudes. If their frequency is too large, they may deposit huge amount of energy in the ambient atmosphere locally as well as globally so it has to be accounted for further studies. It should also be noted that approximately 17% of CGRO/BATSE events previously identified as TGFs were in fact beams of electrons and positrons with energies extending above 30 MeV[34].

These energetic electrons and positrons are produced due to Compton scattering and pair production of γ-rays of TGFs and 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. These events generally last long (~30 milliseconds) as compared to TGFs which have typically 1 millisecond duration. One should be able to separate these energetic particle beams from TGFs for the exact calculation of their occurrence rate.

Using the analysis of low-frequency radio emissions generated by TGFs, the source altitudes of two TGF events were found 11.8±0.4 km and 11.9±0.9 km[27]. This finding describes the source region of TGFs is in the interior of the thunderstorm between the two main charge layers and implies an intrinsic TGF brightness of approximately 10^{18} runaway electrons.

They also observed the current moment waveforms associated with these two TGF-generating process and found their peak currents around 120 kA and >500 kA. This indicates that these TGFs can radiate intensely enough and may create some high altitude (~90 km) optical emissions called "elves" which are known to be generated by electromagnetic pulses of strong lightning strokes.

The measurements on the altitude and time relationship between intracloud (IC) lightning leader development and TGF generation reveals that nearly all TGFs occur after the leader extends 1.5-2 km from its initiation point and takes several steps in 2-3 milliseconds[28]. In three observed events, the highest altitude obtained by lightning leaders before TGFs production was at 11.2, 8.3 and 9.4 km[28].

One interesting question is that why are TGFs not produced in earlier or later stages of the same leader? This may be a feature of TGFs and should be explained by future TGF models. The puzzling dependence of TGFs duration on associated lightning currents that long lasting TGFs are associated with low lightning currents and short lived TGFs are associated with high currents is a mystery till date. The exact source altitude of TGFs remains a basic question. Recently, it is found that TGF-generating process simultaneously produce radio frequency emissions[39]. These TGF associated radio pulses are found essentially identical in pulse shape and occurrence in context to the recently identified positive polarity energetic in-cloud pulses (+EIPs).

EIPs are a recently identified class of high peak-current (>200 kA) lightning events that occur during the progression of lightning in-cloud negative leaders and can be detected and identified on the basis of signals from distant ground-based radio sensors[29]. +EIPs are found directly linked to the TGFs and these are two facets of the same phenomena[71]. However, the radio emission signatures and occurrence contexts of –EIPs are found similar with +EIPs and thus –EIPs may also be associated to downward TGFs[72].

Lyu et al[71] also reported that the chances of +EIP in a TGF ranges from 37% to 100%. So, it is suggested that one can also study TGFs from ground based continuous measurements of EIPs with the help of electromagnetic sensors without the need for accompanying spacecraft gamma-ray observations. We again suggest that more and more observations should be ground-based because these are more sensitive than satellite observations, which detect only the most powerful TGFs. Since ground based detectors are closer to the source of event and one can observe an event with the several detectors, so it can reveal new information about the production of TGFs. The ground-based approach can also identify TGFs in higher-latitude regions both on land and ocean that are beyond the limits of current satellite-based detectors[71].

However, observation of TGFs using ground based experiments are inherently challenging because atmospheric gamma-rays strongly attenuate during their propagation towards ground. The EIPs may produce lower ionospheric optical emissions called elves[66]. EIPs produce large current moment of peak value several hundreds of kA.km of duration tens of microseconds. The radiated electric field due to this current moment at higher altitudes reaches a few times the threshold electric field which excites the optical emissions called elves[66].

Previously, it has been thought that only strong cloud to ground lightning can produce elves. Therefore, the knowledge of the optical characteristics of elves produced by EIPs could be useful to explore possible inception mechanisms of TGFs. Both TGE and TGFs occur just before the lightning activity and hence understanding of these events can reveal the long standing mystery of initiation of lightning.

Conclusion

A comparative study of the calculated TGF spectra using Monte Carlo simulation of runaway breakdown of air and the RHESSI and CGRO/BATSE observations reveals that the source altitude of TGFs must be below 21 km altitude which is lower than the typical minimum sprite altitudes. These results imply that TGFs may not be associated with the red sprites but other high altitude discharges like blue jets and blue starters which are observed to emanate from top of the thunderstorms may be involved. Moreover, the soft energy spectrum seen in some BATSE TGFs is inconsistent with such large atmospheric depths, indicating that there may exist two distinct sources of TGFs, with altitudes below 21 km and above 30 km.

Recently Xu et al[118] described theoretically that when TGF passes through the atmosphere, it may generate an excited species of neutral and ionized molecules via collisions between γ-photons and air molecules leading to significant amount of optical emission. They named them novel type of transient luminous events which may be seen near the cloud tops.

According to them, this predicted phenomenon may illuminate a region with a size larger than the TGF source and has detectable levels of brightness. The measurements of these novel types of transient luminous events may provide us much detailed information of TGFs and their associated lightning.

However, the most compelling question about TGFs and related phenomena is whether these events are relatively rare and linked to a specific class of lightning, or pervasive and possibly associated to every lightning discharge. Most of the TGFs are believed that they occur inside thunderclouds during the initial stage of the intracloud (IC) lightning.

However, how the lightning is connected to the production of TGFs? Why some of the lightning produces TGFs while many others do not? What are the critical conditions under which TGFs are generated? The altitude range in which they can be produced; the spatial extent of their source regions and the angular distribution of photons of TGFs; how frequent they are and whether they are hazardous to any spacecraft or airline passenger and crew? Why most of the TGFs occur during the decline of flash rate production? Why

TGFs are mostly associated with high altitude thunderstorms?

These are the basic questions which should be investigated in near future to understand the relation between TGFs, lightning and thunderstorms and hence a detailed analytical study along with simulation work is needed to know the exact underlying mechanisms and physical properties of these high energy atmospheric events.

Acknowledgement

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References

1. Abbasi R., Belz J., Von R. L., Rodeheffer D., Krehbiel P., Remington J. and Rison W., Ground-based observations of terrestrial gamma ray flashes associated with downward-directed lightning leaders, *EPJ Web of Conferences*, **197**, 03002 **(2019)**

2. Abbasi R.U. et al, Gamma ray showers observed at ground level in coincidence with downward lightning leaders, *Journal of Geophysical Research: Atmosphere*, **123(13)**, 6864-6879 **(2018)**

3. Albrechtsen K.H., Østgaard N., Berge N. and Gjesteland J., Observationally weak TGFs in the RHESSI data, *Journal of Geophysical Research-Atmosphere*, **124**, 287-298 **(2019)**

4. Atwood W.B. et al, The large area telescope on the Fermi gamma-ray space telescope mission, *The Astrophysical Journal*, **697**, 1071-1102 **(2009)**

5. Babich L.P., Bochkov E.I., Donskoi E.N. and Kutsyk I.M., Source of prolonged bursts of high-energy gamma rays detected in thunderstorm atmosphere in Japan at the coastal area of the Sea of Japan and on high mountaintop, *Journal of Geophysical Research*, **115**, A09317 **(2010)**

6. Bell T.F., Pasko V.P. and Inan U.S., Runaway electrons as a source of red sprites in the mesosphere, *Geophysical Research Letters*, **22**, 2127-2130 **(1995)**

7. Bogomolov V.V., Panasyuk M.I., Svertilov S.I., Bogomolov A.V., Garipov G.K., Iyudin A.F., Klimov P.A., Klimov S.I., Mishieva T.M., Minaev P. Yu., Morozenko V.S., Morozov O.V., Posanenko A.S., Prokhorov A.V. and Rotkel H., Observation of terrestrial gamma-ray flashes in the RELEC space experiment on the Vernov satellite, *Cosmic Research*, **55**, 159-168 **(2017)**

8. Bowers G.S., Smith D.M., Kelley N.A., Martinez-Mckinney G.F., Cummer S.A., Dwyer J.R., Heckman S., Holzworth R.H., Marks F., Reasor P., Gamache J., Dunion J., Richards T. and Rassoul H.K., A terrestrial gamma-ray flash inside the eyewall of Hurricane Patricia, *Journal of Geophysical Research: Atmosphere*, **123(10)**, 4977-4987 **(2018)**

9. Briggs M.S., Fishman G.J., Connaughton V., Bhat P.N., Paciesas W.S., Preece R.D., Wilson-Hodge C., Chaplin V.L., Kippen R.M., Kienlin A.V., Meegan C.A., Bissaldi E., Dwyer J.R., Smith D.M., Holzworth R.H., Grove J.E. and Chekhtman A., First results on terrestrial gamma-ray flashes from the Fermi Gamma-ray burst monitor, *Journal of Geophysical Research*, **115**, A07323 **(2010)**

10. Briggs M.S., Connaughton V., Wilson-Hodge C., Preece R.D., Fishman G.J., Kippen R.M., Bhatt P.N., Paciesas W.S., Chaplin V.L., Meegan C.A., Kienlin A.V., Greiner J., Dwyer J.R. and Smith D.M., Electron-positron beams from terrestrial lightning observed with Fermi GBM, *Geophysical Research Letters*, **38**, L02808 **(2011)**

11. Briggs M.S. et al, Terrestrial gamma-ray flashes in the Fermi era: Improved observations and analysis methods, *Journal of Geophysical Research-Space Physics*, **118**, 3805-3830 **(2013)**

12. Brunetti M., Cecchini S., Galli M., Giovannini G. and Pagliarin A., Gamma-ray bursts of atmospheric origin in the MeV energy range, *Geophysical Research Letters*, **27(11)**, 1599-1602 **(2000)**

13. Carlson B.E., Lehtinen N.G. and Inan U.S., Constraints on terrestrial gamma-ray flash production from satellite observations, *Geophysical Research Letters*, **34**, L08809 **(2007)**

14. Carlson B.E., Lehtinen N.G. and Inan U.S., Terrestrial gamma ray flash production by lightning current pulses, *Journal of Geophysical Research*, **114**, A00E08 **(2009)**

15. Carlson B.E., Lehtinen N.G. and Inan U.S., Neutron production in terrestrial gamma ray flashes, *Journal of Geophysical Research-Space Physics*, **115**, A00E19 **(2010)**

16. Carlson B.E., Lehtinen N.G. and Inan U.S., Terrestrial gamma ray flash production by active lightning leader channels, *Journal of Geophysical Research*, **115**, A10324 **(2010)**

17. Celestin S., Xu W. and Pasko V.P., Terrestrial gamma ray flashes with energies up to 100 MeV produced by nonequilibrium acceleration of electrons in lightning, *Journal of Geophysical Research*, **117**, A05315 **(2012)**

18. Chilingarian A., Daryan A., Arakelyan K., Hovhannisyan A., Mailyan B., Melkumyan L., Hovsepyan G., Chilingaryan S., Reymers A. and Vanyan L., Ground-based observations of thunderstorm-correlated fluxes of high-energy electrons, gamma rays andneutrons, *Physical Review D*, **82**, 043009 **(2010)**

19. Chilingarian A., Thunderstorm ground enhancements-Model and relation to lightning flashes, *Journal of Atmospheric and Solar Terrestrial Physics*, **107**, 68-76 **(2014)**

20. Chilingarian A., Chilingaryan S. and Reymers A., Atmospheric discharges and particle fluxes, *Journal of Geophysical Research: Space Physics*, **120**, 5845-5853 **(2015)**

21. Chilingarian A., Khanikyants Y., Mareev E., Pokhsraryan D., Rakov V. and Soghomonyan S., Types of lightning discharges that abruptly terminate enhanced fluxes of energetic radiation and particles observed at ground level, 6th International TEPA Symposium, Oct, 03-07, Armenia **(2016)**

22. Chilingarian A., Mkrtchyan H., Karapetyan G., Chilingaryan S., Sargsyan B. and Arestakesyan A., Catalog of 2017 Thunderstorm Ground Enhancement (TGE) events observed on Aragats, *Scientific Reports*, **9(1)**, 6253 **(2019)**

23. Cohen M.B., Inan U.S. and Fishman G., Terrestrial gamma-ray flashes observed aboard the Compton Gamma Ray Observatory/Burst and Transient Source Experiment and

ELF/VLF radio atmospherics, *Journal of Geophysical Research*, **111**, D24109 **(2006)**

24. Collier A.B., Gjesteland T. and Østgard N., Assessing the power law distribution of TGFs, *Journal of Geophysical Research*, **116**, A10320 **(2011)**

25. Connaughton V. et al, Radio signals from electron beams in terrestrial gamma ray flashes, *Journal of Geophysical Research-Space Physics*, **118**, 2313-2320 **(2013)**

26. Cummer S.A., Zhai Y., Hu W., Smith D.M., Lopez L.I. and Stanley M.A., Measurements and implications of the relationship between lightning and terrestrial gamma ray flashes, *Geophysical Research Letters*, **32**, L08811 **(2005)**

27. Cummer S.A., Briggs M.S., Dwyer J.R., Xiong S., Connaughton V., Fishman G.J., Lu G., Lyu F. and Solanki R.K., The source altitude, electric currents and intrinsic brightness of terrestrial gamma ray flashes, *Geophysical Research Letters*, **41**, 8586-8593 **(2014)**

28. Cummer S.A., Lyu F., Briggs M.S., Fitzpatrick G., Roberts O.J. and Dwyer J.R., Lightning leader altitude progression in terrestrial gamma-ray flashes, *Geophysical Research Letters*, **42**, 7792-7798 **(2015)**

29. Cummer S.A., Lyu F., Briggs M.S., Cramer E., Stanbro M., Roberts O. and Smith D.M., The connection between terrestrial gamma-ray flashes and energetic in-cloud lightning pulses, AGU Fall Meeting Abstracts **(2017)**

30. Dwyer J.R., A fundamental limit on electric fields in air, *Geophysical Research Letters*, **30(20)**, 2055 **(2003)**

31. Dwyer J.R., Rassoul H.K., Al-Dayeh M., Caraway L., Wright B., Chrest W., Uman M.A., Rakov V.A., Rambo K.J., Jordan D.M., Jerauld J. and Smyth C., A ground level gamma-ray burst observed in association with rocket-triggered lightning, *Geophysical Research Letters*, **31**, L05119 **(2004)**

32. Dwyer J.R. and Smith D.M., A comparison between Monte Carlo simulations of runaway breakdown and terrestrial gamma-ray flash observations, *Geophysical Research Letters*, **32**, L22804 **(2005)**

33. Dwyer J.R., Relativistic breakdown in planetary atmosphere, *Physics of Plasmas*, **14**, 042901 **(2007)**

34. Dwyer J.R., Grefenstette B.W. and Smith D.M., High energy electron beams launched into space by thunderstorms, *Geophysical Research Letters*, **35**, L02815 **(2008)**

35. Dwyer J.R., The relativistic feedback discharge model of terrestrial gamma ray flashes, *Journal of Geophysical Research: Space Physics*, **117**, A02308 **(2012)**

36. Dwyer J.R., Smith D.M. and Cummer S.A., High-energy atmospheric physics: terrestrial gamma-ray flashes and related phenomena, *Space Science Review*, **173**, 133-196 **(2012)**

37. Dwyer J.R. and Cummer S.A., Radio emissions from terrestrial gamma-ray flashes, *Journal of Geophysical Research-Space Physics*, **118**, 3769-3790 **(2013)**

38. Dwyer J.R., Liu N. and Rassoul H.K., Properties of the thundercloud discharges responsible for terrestrial gamma-ray flashes, *Geophysical Research Letters*, **40(15)**, 4067-4073 **(2013)**

39. Dwyer J.R. and Uman M.A., The Physics of lightning, *Physics Reports*, **534(4)**, 147-241 **(2014)**

40. Eack K.B. and Beasley W.H., Long-duration X-ray emissions observed in thunderstorms, *Journal of Geophysics Research: Atmosphere*, **120**, 6887-6897 **(2015)**

41. Enoto T., Wada Y., Furuta Y., Nakazawa K., Yuasa T., Okuda K., Makishima K., Sato M., Sato Y., Nakano T., Umemoto D. and Tsuchiya H., Photonuclear reactions triggered by lightning discharge, *Nature*, **551**, 481-484 **(2017)**

42. European Space Agency, First-ever constructed image of a terrestrial gamma-ray flash, https://phys.org/news/2019-05-first-ever-image-terrestrial-gamma-ray.html **(2019)**

43. Fabró F., Montanyà J., Marisaldi M., Van Der Velde O.A. and Fuschino F., Analysis of global Terrestrial Gamma Ray Flashes distribution and special focus on AGILE detections over South America, *Journal of Atmospheric and Solar Terrestrial Physics*, **124**, 10-20 **(2015)**

44. Fishman G.J., Bhat P.N., Mallozzi R., Horack J.M., Koshut T., Kouveliotou C., Pendleton G.N., Meegan C.A., Wilson R.B., Paciesas W.S., Goodman S.J. and Christian H.J., Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, **264**, 1313-1316 **(1994)**

45. Foley S. et al, Pulse properties of terrestrial gamma-ray flashes detected by the Fermi Gamma-Ray Burst Monitor, *Journal of Geophysical Research-Space Physics*, **119**, 5931-5942 **(2014)**

46. Gjesteland T., Østgaard N., Collier A.B., Carlson B.E., Cohen M.B. and Lehtinen N.G., Confining the angular distribution of terrestrial gamma ray flash emission, *Journal of Geophysical Research*, **116**, A11313 **(2011)**

47. Gjesteland T., Østgaard N., Collier A.B., Carlson B.E., Eyles C. and Smith D.M., A new method reveals more TGFs in the RHESSI data, *Geophysical Research Letters*, **39**, L05102 **(2012)**

48. Gjesteland T., Properties of terrestrial gamma ray flashes, Ph.D. Thesis, Department of Physics and Technology, University of Bergen, Norway **(2012)**

49. Gjesteland T., Østgaard N., Bitzer P. and Christian H.J., On the timing between terrestrial gamma ray flashes, radio atmospherics and optical lightning emission, *Journal of Geophysical Research-Space Physics*, **122**, 7734-7741 **(2017)**

50. Grefenstette B.W., Smith D.M., Hazelton B.J. and Lopez L.I., First RHESSI terrestrial gamma ray flash catalog, *Journal of Geophysical Research*, **114**, A02314 **(2009)**

51. Gurevich A.V., Milikh G.M. and Roussel-Dupre R., Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Physics Letters A*, **165**, 463-468 **(1992)**

52. Gurevich A.V. and Zybin K.P., Runaway breakdown and electric discharges in thunderstorms, *Physics-Uspekhi*, **44(11)**, 1119-1140 **(2001)**

53. Gurevich A.V., Chubenko A.P., Karashtin A.N., Mitko G.G., Naumov A.S., Ptitsyn M.O., Ryabov V.A., Shepetov A.L., Shlyugaev Yu V., Vildanova L.I. and Zybin K.P., Gamma-ray emission from thunderstorm discharges, *Physics Letters A*, **375**, 1619-1625 **(2011)**

54. Hare B.M., Uman M.A., Dwyer J.R., Jordan D.M., Biggerstaff M.I., Caicedo J.A., Carvalho F.L., Wilkes R.A., Kotovsky D.A., Gamerota W.R., Pilkey J.T., Ngin T.K., Moore R.C., Rassoul H.K., Cummer S.A., Grove J.E., Nag A., Betten D.P. and Bozarth A., Ground-level observation of a terrestrial gamma ray flash initiated by a triggered lightning, *Journal of Geophysical Research-Atmosphere*, **121**, 6511-6533 **(2016)**

55. Inan U.S., Reising S.C., Fishman G.J. and Horack J.M., On the association of terrestrial gamma-ray bursts with lightning and implications for sprites, *Geophysical Research Letters*, **23**, 1017-1020 **(1996)**

56. Inan U.S. and Lehtinen N.G., Production of terrestrial gamma-ray flashes by an electromagnetic pulse from a lightning return stroke, *Geophysical Research Letters*, **32**, L19818 **(2005)**

57. Inan U.S., Cohen M.B., Said R.K., Smith D.M. and Lopez L.I., Terrestrial gamma ray flashes and lightning discharges, *Geophysical Research Letters*, **33**, L18802 **(2006)**

58. Kelley N.A., Smith D.M., Dwyer J.R., Splitt M., Lazarus S., Martinez-McKinney F., Hazelton B., Grefenstette B., Lowell A. and Rassoul H.K., Relativistic electron avalanches as a thunderstorm discharge competing with lightning, *Nature Communications*, **6**, doi: 10.1038/ncomms8845 **(2015)**

59. Kochkin P., Deursen A.P.J., Van Marisaldi M., Ursi A., De Boer A.I., Bardet M., Allasia C., Boissin J.F., Flourens F. and Østgaard N., In-Flight Observation of Gamma Ray Glows by ILDAS, *Journal of Geophysical Research: Atmosphere*, **122(23)**, 12801-12811 **(2017)**

60. Krider E.P., On the electromagnetic fields, Poynting vector andpeak power radiated by lightning return strokes, *Journal of Geophysical Research*, **97(D14)**, 15913-15917 **(1992)**

61. Kuroda Y., Oguri S., Kato Y., Nakata R., Inoue Y., Ito C. and Minowa M., Observation of gamma ray bursts at ground level under the thunderclouds, *Physics Letters B*, **758**, 286-291 **(2016)**

62. Lehtinen N.G., Bell T.F. and Inan U.S., Monte Carlo simulation of runaway MeV electron breakdown with application to red sprites and terrestrial gamma ray flashes, *Journal of Geophysical Research: Space Physics*, **104(A11)**, 24699-24712 **(1999)**

63. Lehtinen N.G., Inan U.S. and Bell T.F., Effects of thunderstorm driven runaway electrons in the conjugate hemisphere: Purple sprites, ionization enhancements andgamma rays, *Journal of Geophysical Research*, **106**, 28841-28856 **(2001)**

64. Li X.Q., Jiang R.B., Zheng Y., Zhou H.Z., Xing B., Li Y.N. and Liu W., Ground-level observation of terrestrial gamma-ray bursts initiated by lightning, 2017 Sixth Asia-Pacific Conference on Antennas and Propagation, China **(2017)**

65. Lindy N.C., Benton E.R., Beasley W.H. and Petersen D.A., Energetic cosmic-ray secondary electron distribution at thunderstorm altitudes, *Journal of Atmospheric and Solar Terrestrial Physics*, **179**, 435-440 **(2018)**

66. Liu N., Dwyer J.R. and Cummer S.A., Elves accompanying terrestrial gamma ray flashes, *Journal of Geophysical Research*, **122**, 10563-10576 **(2017)**

67. López J.A., Montanyà J., Van Der Velde O.A., Pineda N., Salvador A., Romero D., Aranguren D. and Taborda J., Charge structure of two tropical thunderstorms in Colombia, *Journal of Geophysical Research: Atmosphere*, **124(10)**, 5503-5515 **(2019)**

68. Lu G., Blakeslee R.J., Li J., Smith D.M., Shao X.M., McCaul E.W., Buechler D.E., Christian H.J., Hall J.M. and Cummer S.A., Lightning mapping observation of a terrestrial gamma-ray flash, *Geophysical Research Letters*, **37(11)**, L11806 **(2010)**

69. Lu G., Cummer S.A., Li J., Han F., Smith D.M. and Grefenstette B.W., Characteristics of broadband lightning emissions associated with terrestrial gamma ray flashes, *Journal of Geophysical Research*, **116**, A03316 **(2011)**

70. Lu G., Zhang H., Cummer S.A., Wang Y., Lyu F., Briggs M., Xiong S. and Chen A., A comparative study on the lightning sferics associated with terrestrial gamma-ray flashes observed in Americas and Asia, *Journal of Atmospheric and Solar Terrestrial Physics*, **183**, 67-75 **(2019)**

71. Lyu F., Cummer S.A., Briggs M., Marisaldi M., Blakeslee R.J., Bruning E., Wilson J.G., Rison W., Krehbiel P., Lu G., Cramer E., Fitzpatrick G., Mailyan B., McBreen S., Roberts O.J. and Stanbro M., Ground detection of terrestrial gamma ray flashes from distant radio signals, *Geophysical Research Letters*, **43**, 8728-8734 **(2016)**

72. Lyu F. and Cummer S.A., Energetic radio emissions and possible terrestrial gamma-ray flashes associated with downward propagating negative leaders, *Geophysical Research Letters*, **45(19)**, 10764-10771 **(2018)**

73. Marisaldi M. et al, Detection of terrestrial gamma ray flashes up to 40 MeV by the AGILE satellite, *Journal of Geophysical Research*, **115**, A00E13 **(2010)**

74. Marisaldi M. et al, Enhanced detection of terrestrial gamma-ray flashes by AGILE, *Geophysical Research Letters*, **42**, 9481-9487 **(2015)**

75. Marisaldi M., Østgaard N., Neubert T., Reglero V. and ASIM team and collaborators, ASIM-Fermi simultaneous observation of terrestrial gamma-ray flashes, *Geophysical Research Abstracts-EGU general Assembly*, **21**, EGU2019-7625 **(2019)**

76. Marshall T.C., Stolzenburg M., Maggio C.R., Coleman L.M., Krehbiel P.R., Hamlin T., Thomas R.J. and Rison W., Observed electric fields associated with lightning initiation, *Geophysical Research Letters*, **32**, L03813 **(2005)**

77. McCarthy M. and Parks G.K., Further observations of X-rays inside thunderstorms, *Geophysical Research Letters*, **12(6)**, 393-396 **(1985)**

78. Moss G.D., Pasko V.P., Liu N. and Veronis G., Monte Carlo model for analysis of thermal runaway electrons in streamer tips in

transient luminous events and streamer zones of lightning leaders, *Journal of Geophysical Research*, **111**, A02307 **(2006)**

79. Nemiroff R.J., Jerry T.B. and Norris J.P., Temporal and spectral characteristics of terrestrial gamma flashes, *Journal of Geophysical Research*, **102(A5)**, 9659-9665 **(1997)**

80. Neubert T., Østgaard N., Reglero V., Blanc E., Chanrion O., Oxborrow C.A., Orr A., Tacconi M., Hartnack O. and Bhanderi Dan D.V., The ASIM mission on the international space station, *Space Science Reviews*, **215,** 26 **(2019)**

81. Neubert T. et al, A terrestrial gamma-ray flash and ionospheric ultraviolet emissions powered by lightning, *Science*, **367(6474)**, 183-186 **(2020)**

82. Østgaard N., Gjesteland T., Stadsnes J., Connell P.H. and Carlson B., Production altitude and time delays of the terrestrial gamma flashes: Revisiting the Burst and Transient Source Experiment spectra, *Journal of Geophysical Research: Space Physics*, **113**, A02307 **(2008)**

83. Østgaard N., Gjesteland T., Hansen R.S., Collier A.B. and Carlson B., The true fluence distribution of terrestrial gamma ray flashes at satellite altitude, *Journal of Geophysical Research*, **117**, A03327 **(2012)**

84. Østgaard N., Gejesteland T., Carlson B.E., Collier A.B., Cummer S.A., Lu G. and Christian H.J., Simultaneous observations of optical lightning and terrestrial gamma ray flash from space, *Geophysical Research Letters*, **40**, 2423-2426 **(2013)**

85. Østgaard N., Albrecthsen K.H., Gjesteland T. and Collier A., A new population of terrestrial gamma-ray flashes in the RHESSI data, *Geophysical Research Letters*, **42**, 10937-10942 **(2015)**

86. Panasyuk M.I. et al, RELEC mission: Relativistic electron precipitation and TLE study on-board small spacecraft, *Advances in Space Research*, **57**, 835-849 **(2016)**

87. Paras M.K. and Rani P., Survey on electrical activity in Earth's atmosphere, *Advanced Electromagnetics*, **7**, 34-45 **(2018)**

88. Parks G.K., Mauk B.H., Spiger R. and Chin J., X-ray enhancements detected during thunderstorm and lightning activities, *Geophysical Research Letters*, **8(11)**, 1176-1179 **(1981)**

89. Pasko V.P., Inan U.S. and Bell T.F., Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere, *Journal of Geophysical Research*, **102(A3)**, 4529-4561 **(1997)**

90. Raizer Yu P., Gas discharge Physics, Springer, New York **(1991)**

91. Raizer Yu. P., Milikh G.M., Shneider M.N. and Novakovski S.V., Long streamers in the upper atmosphere above thundercloud, *Journal of Physics D: Applied Physics*, **31**, 3255-3264 **(1998)**

92. Reising S.C., Inan U.S., Bell T.F. and Lyons W.A., Evidence for continuing current in sprite-producing cloud-to-ground lightning, *Geophysical Research Letters*, **23**, 3639-3642 **(1996)**

93. Ringuette R., Case G.L., Cherry M.L., Granger D., Guzik T.G., Stewart M. and Wefel J.P., TETRA observation of gamma-rays at ground level associated with nearby thunderstorms, *Journal of Geophysical Research-Space Physics*, **118(12)**, 7841-7849 **(2013)**

94. Roberts O.J., Fitzpatrick G., Priftis G., Bedka K., Chronis T., McBreen S., Briggs M.S., Cramer E., Mailyan B. and Stanbro M., Terrestrial gamma-ray flashes due to particle acceleration in tropical storm systems, *Journal of Geophysical Research-Atmosphere*, **122**, 3374-3395 **(2017)**

95. Roberts O.J., Fitzpatrick G., Stanbro M., McBreen S., Briggs M.S., Holzworth R.H., Grove J.E., Chekhtman A., Cramer E.S. and Mailyan B.G., The First Fermi-GBM Terrestrial Gamma Ray Flash Catalog, *Journal of Geophysical Research-Space Physics*, **123**, 4381-4401 **(2018)**

96. Rutjes C., Diniz G., Ferreira I.S. and Ebert U., TGF Afterglows: A new radiation mechanism from thunderstorms, *Geophysical Research Letters*, **44(20)**, 10702-10712 **(2017)**

97. Shao X.M., Hamlin T. and Smith D.M., A closer examination of terrestrial gamma-ray flash-related lightning processes, *Journal of Geophysical Research- Space Physics*, **115**, A00E30 **(2010)**

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

99. Smith D.M., Hazelton B.J., Grefenstette B.W., Dwyer J.R., Holzworth R.H. and Lay E.H., Terrestrial gamma ray flashes correlated to storm phase and tropopause height, *Journal of Geophysical Research: Space Physics*, **115**, A00E49 **(2010)**

100. Smith D.M. et al, The rarity of terrestrial gamma-ray flashes, *Geophysical Research Letters*, **38**, L08807 **(2011)**

101. Smith D.M. et al, A terrestrial gamma ray flash observed from an aircraft, *Journal of Geophysical Research*, **116**, D201124 **(2011)**

102. Smith D.M., Bowers G.S., Kamogawa M., Wang D., Ushio T., Ortberg J., Dwyer J.R. and Stock M., Characterizing upward lightning with and without a terrestrial gamma ray flash, *Journal of Geophysical Research- Atmosphere*, **123(20)**, 11321-11332 **(2018)**

103. Splitt M.E., Lazarus S.M., Barnes D., Dwyer J.R., Rassoul H.K., Smith D.M., Hazelton B. and Grefenstette B., Thunderstorm characteristics associated with RHESSI identified terrestrial gamma ray flashes, *Journal of Geophysical Research*, **115**, A00E38 **(2010)**

104. Stanley M.A., Shao X.M., Smith D.M., Lopez L.I., Pongratz M.B., Harlin J.D., Stock M. and Regan A., A link between terrestrial gamma-ray flashes and intracloud lightning discharges, *Geophysical Research Letters*, **33**, L06803 **(2006)**

105. Tavani M. et al, The AGILE Mission, *Astronomy and Astrophysics*, **502**, 995-1013 **(2009)**

106. Tavani M. et al, Terrestrial gamma-ray flashes as powerful particle accelerators, *Physical Review Letters*, **106(1)**, 018501 **(2011)**

107. Tavani M., Argan A., Paccagnella A., Pesoli A., Palma F., Gerardin S., Bagatin M., Trois A., Picozza P., Benvenuti P., Flamini E., Marisaldi M., Pittori C. and Giommi P., Possible effects on avionics induced by terrestrial gamma-ray flashes, *Natural Hazards and Earth System Sciences*, **13**, 1127-1133 **(2013)**

108. Tierney D., Briggs M.S., Fitzpatrik G., Chaplin V.L., Foley S., McBreen S., Connaughton V., Xiong S., Byrne D., Carr M., Bhat P.N., Fishman G.J., Greiner J., Kippen R.M., Megan C.A., Paciesas W.S., Preece R.D., Von Kienlin A. and Wilson-Hodge C., Fluence distribution of terrestrial gamma ray flashes observed by the Fermi Gamma-ray Burst Monitor, *Journal of Geophysical Research-Space Physics*, **118**, 6644-6650 **(2013)**

109. Tran M.D., Rakov V.A., Mallick S., Dwyer J.W., Nag A. and Heckman S., A terrestrial gamma-ray flash recorded at the Lightning Observatory in Gainesville, Florida, *Journal of Atmospheric and Solar-Terrestrial Physics*, **136**, 86-93 **(2015)**

110. Tsuchiya H., Enoto T., Iwata K., Yamada S., Yuasa T., Kitaguchi T., Kawaharada M., Nakazawa K., Kokubun M., Kato H., Okano M., Tamagawa T. and Makishima K., Hardening and termination of long-duration γ rays detected prior to lightning, *Physical Review Letters*, **111**, 015001 **(2013)**

111. Ursi A., Marisaldi M., Tavani M., Casella D., Sanò P. and Dietrich S., Detection of multiple terrestrial gamma-ray flashes from thunderstorm systems, *Journal of Geophysical Research-Space Physics*, **121**, 11302-11315 **(2016)**

112. Vodopiyanov I.B., Dwyer J.R., Cramer E.S., Lucia R.J. and Rassoul H.K., The effect of direct electron-positron pair production on relativistic feedback rates, *Journal of Geophysical Research: Space Physics*, **120(1)**, 800-806 **(2015)**

113. Wada Y., Bowers G.S., Enoto T., Kamogawa M., Nakamura Y., Morimoto T., Smith D.M., Furuta Y., Nakazawa K., Yuasa T., Matsuki A., Kubo M., Tamagawa T., Makishima K. and Tsuchiya H., Termination of electron acceleration in thundercloud by intracloud/intercloud discharge, *Geophysical Research Letters*, **45**, 5700-5707 **(2018)**

114. Wada Y., Enoto T., Nakamura Y., Furuta Y., Yuasa T., Nakazawa K., Morimoto T., Sato M., Matsumoto T., Yonetoku D., Sawano T., Sakai H., Kamogawa M., Ushio T., Makishima K. and Tsuchiya H., Gamma-ray glow preceding downward terrestrial gamma-ray flash, *Communications Physics*, **2(1)**, 67, DOI: 10.1038/s42005-019-0168-y **(2019)**

115. Williams E. et al, Lightning flashes conducive to the production and escape of gamma radiation to space, *Journal of Geophysical Research*, **111**, D16209 **(2006)**

116. Wilson C.T.R., The acceleration of β-particles in strong electric fields such as those of thunderclouds, Mathematical Proceedings of Cambridge Philosophical Society, 534-538 **(1925)**

117. Xu W., Celestin S. and Pasko V.P., Optical emissions associated with terrestrial gamma ray flashes, *Journal of Geophysical Research-Space Physics*, **120**, 1355-1370 **(2014)**

118. Xu W., Celestin S., Pasko V.P. and Marshall R.K., A novel type of transient luminous events produced by terrestrial gamma-ray flashes, *Geophysical Research Letters*, **44**, 2571-2578 **(2017)**.

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