

Runaway processes in the upper and lower atmosphere: a change of paradigm

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Abstract

Relativistic Runaway Electron Avalanches (RREA) are central to understanding a spectrum of high-energy atmospheric phenomena, including Terrestrial Gamma-ray Flashes (TGFs), Thunderstorm Ground Enhancements (TGEs), and gamma-ray glows. Despite their common physical origin, these events are often treated separately due to differences in detection methods, duration, and altitude. In this work, we present a unified conceptual and observational framework that reinterprets these radiation bursts as manifestations of the same runaway processes occurring in distinct atmospheric layers. Integrating recent results from satellite (ASIM), aircraft (ALOFT), balloon (HELEN), and ground-based (SEVAN) experiments, we demonstrate consistent spectral and temporal behavior across scales. We propose a rational revision of current terminology and challenge longstanding models that attribute TGFs to lightning leader dynamics. This study resolves key contradictions in the field, establishes new classification criteria based on physics rather than detector geometry, and reshapes our understanding of particle acceleration in thunderstorms.

Key Points:

- **Unified physical mechanism:** TGFs, TGEs, and gamma glows are all products of the RREA process occurring in different atmospheric regions.
- **Multi-platform data synthesis:** Includes results from ASIM (space), ALOFT (aircraft), HELEN (balloon), and SEVAN (ground).
- **Terminology update proposed:** Rejects "downward TGFs" and advocates a physically grounded classification system.
- **Challenges prevailing models:** Shows that lightning leader-based models of TGF generation are inconsistent with recent data.
- **Impact:** Offers a paradigm shift in the interpretation of high-energy atmospheric radiation, with implications for space weather, aviation safety, and radiation belt modeling.

1. Introduction

Thunderstorms create strong electric fields that extend across large areas within and around the storm system. Charge separation in thunderclouds, driven by updrafts of warm air and interactions among hydrometeors, generates oppositely directed dipoles within the cloud. From 1945 to 1949, Joachim Kuettner conducted groundbreaking experiments at Zugspitze (Kuettner, 1950), where he discovered the tripole charge structure within thundercloud layers. According to

the tripole model, the atmospheric electric field comprises upper and lower dipoles, accelerating free electrons toward open space and the Earth's surface.

The upper dipole consists of the main negative and positive charge layers in the middle and top of a thundercloud. Electrons create avalanches in the upper atmosphere, producing bremsstrahlung gamma rays. The gamma-ray glows, generated in the upper atmosphere, are detected by airborne experiments flying above thunderstorms (Kelly et al., 2015; Ostgaard et al., 2019; Marisaldi et al., 2024; Helmerich et al., 2024). The most energetic gamma rays occasionally reach orbiting gamma observatories 400-700 km from the source, registering microsecond bursts of particles known as terrestrial gamma flashes (TGFs, Fishman et al., 1994; Mailyan et al., 2015).

The lower dipole comprises the main negative layer and an induced mirror charge in the Earth's surface. A third dipole forms between the main negative layer and a transient "pocket" of positively charged particles in the lower part of the cloud (LPCR), which is often associated with falling graupel (snow pellets coated with a layer of ice, Kuettner, 1950). Electrons accelerated in 2 lower dipoles create electron-gamma ray avalanches detected on the ground as thunderstorm ground enhancements (TGEs, Chilingarian et al., 2010; 2011), comprising millions of gamma rays, electrons, and neutrons. A fourth dipole between the LPCR and its mirror in the Earth accelerates positrons and positive muons while decelerating electrons and negative muons. Understanding these distinct charge structures and the hierarchy of particle acceleration mechanisms helps explain the high-energy phenomena observed in thunderstorms and their implications for atmospheric science.

Particle detectors located beneath electron accelerators at high-altitude sites in Armenia, Eastern Europe, Germany, and elsewhere have recorded hundreds of TGEs, confirming extensive particle fluxes over thousands of square kilometers and durations from seconds to tens of minutes (Chum et al., 2020; Chilingarian et al., 2024a). Data from Aragats have convincingly validated the RREA/TGE model through direct electron and gamma-ray spectrum measurements, observing atmospheric neutrons and positrons (Chilingarian et al., 2012; Chilingarian et al., 2024b). Crucially, these measurements show good agreement with predicted energy spectra and emphasize the role of seed electrons from extensive air showers (EAS, Auger et al., 1939).

Free electrons are abundant in the troposphere. The height of electron maximum density, the so-called Regener–Pfotzer maximum, depends on the geomagnetic cutoff rigidity (R_c), the type of detected particles, and the strength and phase of the solar cycle. Recent measurements, confirmed by PARMA4 calculations (Sato, 2016), put the maximum of the charged particle flux in equatorial regions ($R_c = 10\text{-}15$ GV) at 16-17 km (Fig. 4 of Amrosova et al., 2023). Electric fields, induced by strong thunderstorms, transfer energy to free electrons, accelerate them, and, under special conditions, form electron-photon avalanches. In 1992, Gurevich, Milikh, and Roussel-Dupré formulated conditions for copious multiplication of electrons for each energetic seed electron injected into the strong-field region (Gurevich et al., 1992). This mechanism is now

known as the Relativistic Runaway Electron Avalanche (RREA, Babich et al., 2001; Alexeenko et al., 2002;). A numerical method to solve the relativistic Boltzmann equation for the runaway electron beams (Symbalisty et al., 1998) helps to estimate the threshold (critical) field (Babich et al., 2001; Dwyer et al., 2003) to start RREA. At standard temperature and pressure in dry air at sea level $E_{th} \approx 2.80 \times n$ kV/cm, air density (n) is relative to the sea level one. This threshold field is slightly higher than the breakeven field, corresponding to the minimum ionization energy losses. If the electrons traveled exactly along the electric field lines, this would be the threshold for runaway electron propagation and avalanche multiplication. However, the electrons' trajectories deviate due to Coulomb scattering with atomic nuclei and Møller scattering with atomic electrons, causing deviations from the ideal case. Additionally, secondary electrons from Møller scattering aren't created along the field line, so 20-30% larger electric fields are necessary for electrons to run away and make an avalanche. The recent estimate of the critical field (2,67 kV/cm, Dwyer and Rassoul, 2024) is not a dramatic change because the threshold field at high altitudes depends on fast-changing thunderstorm development and cannot be estimated exactly.

2. Experiments with ASIM and ALOFT facilities

The Atmosphere-Space Interactions Monitor (ASIM, Neubert et al., 2019) on board the International Space Station (ISS) consists of two types of instruments: the X- and gamma-ray spectrometers and the multispectral imaging arrays. The high energy detector (HED) comprises 12 bismuth-germanium-oxide (BGO) bars coupled to a photomultiplier tube (PMT). The temporal resolution of the HED is determined by a dead time of ≈ 550 ns. The optical wide field facilities of ASIM comprise two imaging cameras operated at up to 12 frames per second (337 and 774 nm) and three high-speed photometers at 337 nm (bandwidth 5 nm), 180–230 nm, and 777.4 nm (bandwidth 4 nm) with a 100 kHz sampling rate. The absolute time tagging of the ASIM instruments is not worse than 20 ms, reaching a 10 μ s accuracy when using timestamps from the lightning location networks. Thus, ASIM has unprecedented possibilities to register sequences of particle fluxes and lightning flashes in the upper atmosphere.

The Airborne Lightning Observatory (ALOFT, Ostgaard et al., 2024) in 2023 performed cutting-edge experiments measuring multiple gamma glows from tropical thunderstorms. ALOFT payload consists of five spectrometers, 30 photometers, three electric-field sensors, two radars, and two passive radiometers. Particle fluxes were monitored during flight, and gamma-ray-glowing clouds were identified in real time to return and continue measurements. ALOFT detected more than five hundred gamma-ray glows during nine of the ten flights, showing that thunderclouds can emit gamma rays for hours and over huge regions (see Fig. 1 of Marisaldi et al., 2024). Glows were detected repeatedly following consecutive passages (aircraft revisited flaring thunderclouds after notification of mission physicists) over the same thundercloud system, covering $\approx 10^4$ km².

Correlated measurements of ALOFT and ASIM reveal several gamma-ray fluxes observed by ALOFT but not by ASIM during the ISS overpass. The authors (Bjørge-Engeland et al., 2024) conclude that the overwhelming gamma glow population directed to space from tropical thunderclouds is too weak to be observed from space as TGFs. The source photon brightness of these gamma glows is several orders of magnitude lower than what is usually attributed to TGF observed by orbiting gamma observatories. Thus, TGFs comprise only a small percentage of gamma rays copiously observed above tropical storms.

The ALOFT experiment provided groundbreaking insights, demonstrating that TGFs and Flickering Gamma-ray Flashes (FGFs) were immediately followed by Narrow Bipolar Events (NBEs), initiating significant lightning activity. These findings challenge prior hypotheses that lightning leaders supply the seed electrons for TGFs. Recent measurements from ALOFT23 and long-term nanosecond-scale monitoring at Aragats strongly support an alternative hypothesis: relativistic runaway electron avalanches precede and initiate the lightning leader (Chilingarian et al., 2015; Chilingarian et al., 2017). The combination of gamma-ray imaging and lightning interferometry proposed by this project can directly test and potentially validate this transformative hypothesis.

The ALOFT findings demonstrating the role of thunderclouds as huge natural particle accelerators confirm ground-based observation obtained by continuously monitoring particle fluxes and electric fields within large areas around Aragats Mountain (Chilingarian et al., 2022; Chilingarian et al., 2024c). Thus, the project's implementation will enhance fundamental knowledge of high-energy physics in the atmosphere, clarifying key issues related to particle acceleration and lightning initiation while bridging the gap between HEPA processes in the lower and upper atmosphere (Dwyer et al., 2012).

Ballon flights with radiation detectors were also performed in 2023 and are planned for 2025 (Pallu et al., 2023). The high energy lightning emission network (HELEN) payloads are typically launched on a 1,200g latex weather balloon filled with helium (Helmerich, 2024). Updrafts frequently carried balloons into the storm's center. The radiation detector features a $12 \times 12 \times 20$ mm LYSO: Ce scintillator crystal coupled with a Hamamatsu R6095 photomultiplier tube. During flights, HELEN registered gamma-ray glows lasting up to 2 minutes with increased count rates of more than 10,000 counts per second.

Thus, there is a hierarchy of gamma-ray fluxes above the upper dipole in the thunderous atmosphere. Suppose an aircraft or balloon flies just above a thundercloud. In that case, millions of electrons and gamma rays will be detected, as during TGEs in the lower dipole, coming from an accelerating field 50 m above the Earth's surface. At ALOFT altitudes several kilometers above the source, RREA electrons surely didn't survive, and gamma rays arrived in patches ranging from seconds to minutes. During the largest tropical thunderstorms, only a dozen gamma rays occasionally pass ≈ 500 km to encounter orbiting gamma-ray detectors. During the ALOFT 2024 campaign, among numerous gamma glows, no TGFs were observed by orbiting gamma observatories. Although at a smaller scale, the same hierarchy exists for TGEs: the percent of

electrons in RREA reaching the surface detectors is inversely proportional to the height of the electric field above the detectors. The larger the height, the fewer particles reach the surface, and the smaller the intensity of TGE is. If a storm sustains a strong electric field, the TGE flux continues for minutes, with particles coming uniformly according to Poisson law (Chilingarian et al., 2024d). Recently, it was discovered (Chilingarian et al., 2024a) that electron accelerators in thunderclouds can be astonishingly stable on a minute time scale.

3. Lightning flashes and particle fluxes

Historically, orbiting gamma-ray observatories (400–700 km altitude) detected electron accelerators in thunderclouds indirectly via brief microsecond bursts of gamma rays—occasionally reaching orbiting gamma observatories. However, due to their brevity and very large observational distance, TGFs provided limited insight into physical processes. The recent observations of the ALOFT (Marisaldi et al., 2024; Ostgaard et al., 2024) a few kilometers above gamma-ray sources offer groundbreaking findings, demonstrating the existence of extensive and prolonged gamma-ray emission regions—contrasting with earlier theoretical models used for 30 years to explain TGFs. These newly characterized phenomena, such as Flickering Gamma-ray Flashes (FGFs) and Glow Bursts (GBs), challenge models with very intense local gamma-ray sources and open a fresh frontier in gamma glow/TGF models, making them similar to the RREA/TGE model.

In 2012, the relation between lightning and TGF was thought to be firmly established (Dwyer et al., 2012): “TGFs are produced in what are structurally *normal IC flashes* during the period when the *initial negative polarity leader travels upward* from the main negative charge layer to the upper positive layer. This occurs during the first 5–10 ms of the lightning flash but *distinctly after the flash initiation*. TGFs occur during the ascent of this upward leader before it reaches and expands into the upper positive charge layer. Inferred altitudes of the leader tip at the time of TGF generation have ranged from approximately 11 to 15 km.

In 2024, this relationship seemed to be smeared (Dwyer, Rassoul, 2024): “Currently, TGFs are thought to be produced inside thunderclouds during the initial stage of upward positive intra-cloud (IC) lightning. However, the *relation between lightning and TGF production is unclear*, nor is it well understood why some lightning produces TGFs while others do not. In addition to the spacecraft observations, X-rays and gamma rays have been found to be emitted by thunderclouds using both in situ and ground-based observations. These emissions often form gamma-ray “glows” that *can last from seconds to minutes (thunderstorm ground enhancements when observed from the ground)*. Many of these observations show energy spectra similar to TGFs that extend into the multi-MeV range, indicating similar source mechanisms. “

There is plenty of evidence, starting from the first balloon and NASA’s F-106 jet flights (Parks et al., 1981; McCarthy et al., 1985) to recent aircraft-based observations (Kelley et al., 2015; Kochkin et al., 2017; Ostgaard et al., 2019), that lightning suddenly stops particle fluxes in the upper atmosphere. Lightning flashes in the lower and upper atmosphere abruptly terminate

particle fluxes by lowering the potential difference between charged layers in the cloud. TGEs provide extensive information on particle-lightning relations in the lower atmosphere. Multiyear joint monitoring of atmospheric discharges and particle fluxes on the nanosecond time scale on Aragats proves that TGEs are separated from atmospheric discharges (Chilingarian et al., 2015; 2017a; 2024c). During intense particle fluxes, no nearby discharges are registered within 10 km (Chilingarian and Hovsepyan, 2022). Free electrons from extensive air showers (Auger et al., 1939) are plenty in the atmosphere at each altitude. This source of seed electrons, combined with strong electric fields, sustains electron-gamma ray avalanches below thunderclouds without any exotic sources of seed electrons and special atmospheric discharges.

However, another scenario of lightning-particle flux relation is adopted for the TGF. To justify a TGF model, it is suggested that a small-scale E-field at the lightning leader tip can be strong enough to start RREA and provide abundant seed electrons to create an extremely bright source with up to 10^{20} fluence (cold runaway model, Celestin & Pasko, 2011). However, recent measurements and reanalysis of TGF catalogs do not support the “lightning” scenario of TGF origination (see review Chilingarian, 2024 and references therein). TGFs, measured alongside lightning flash detections by ASIM instruments, occur about 1.4 milliseconds before optical pulses begin (Skeie et al., 2022). In multi-pulse patterns of TGFs registered by ASIM (Fig. 6.6 of Fuglestad, 2023), we can see that the first TGF detected at 18:02:25 on 5 July 2021 smoothly finished, and no optical images of the atmospheric discharges were observed. The second TGF, which occurred 2 ms later, was terminated by a lightning flash, as seen in both the abrupt termination of particle flux and the optical signal. Zhang et al. (2021) showed that gamma rays are produced several ms before a narrow bipolar event (NBE), which often marks the lightning initiation. Analysis of four TGF catalogs from different instruments revealed that a significant proportion of TGFs lead to increased lightning activity detected in radio waves (spherics) between 150-750 ms after TGFs occur (Lindanger et al., 2022). Furthermore, in a recent paper (Gourbin, Celestin, 2024), the maximum achievable number of electrons from “cold runaway” was limited to 10^{17} .

RREA going out from the upper and lower dipoles contains copious electrons, positrons, gamma rays, and neutrons, see Fig. 1. The fluxes directed to open space are possibly more intense than those directed to the Earth’s surface due to possibly larger percentage over the critical value in the upper dipole than in the lower dipole. The RREA flux less attenuates at high altitudes due to the thinning air density, in contrast to the lower dipole, where the increasing air density leads to the fast attenuation of electron flux. The overall brightness of the tropical thundercloud can fulfill the TGF electron fluence requirement to be “at least ten billion times higher than the cosmic ray particles that were passing through the thundercloud” (Dwyer, Rassoul, 2024). Without invoking an exotic source of seed electrons, the fluence of RREA in the upper atmosphere during tropical thunderstorms can reach enormous values. The PARMA4 model (Sato, 2016) estimates electron density at 15 km to be about $10^4/\text{sec m}^2$. Assuming a cloud area of 10^8 m^2 and a gamma glow lasting roughly 3 hours ($\approx 10^4$ seconds), with an RREA multiplication factor of about 10^4 (Dwyer et al., 2012; Chilingarian et al., 2022), we calculate the possible fluence of RREA electrons to reach 10^{20} . Thus, Gamma glows lasting hours over large

tropical systems can naturally amplify cosmic-ray-generated seed electrons to enormous fluences via RREA.

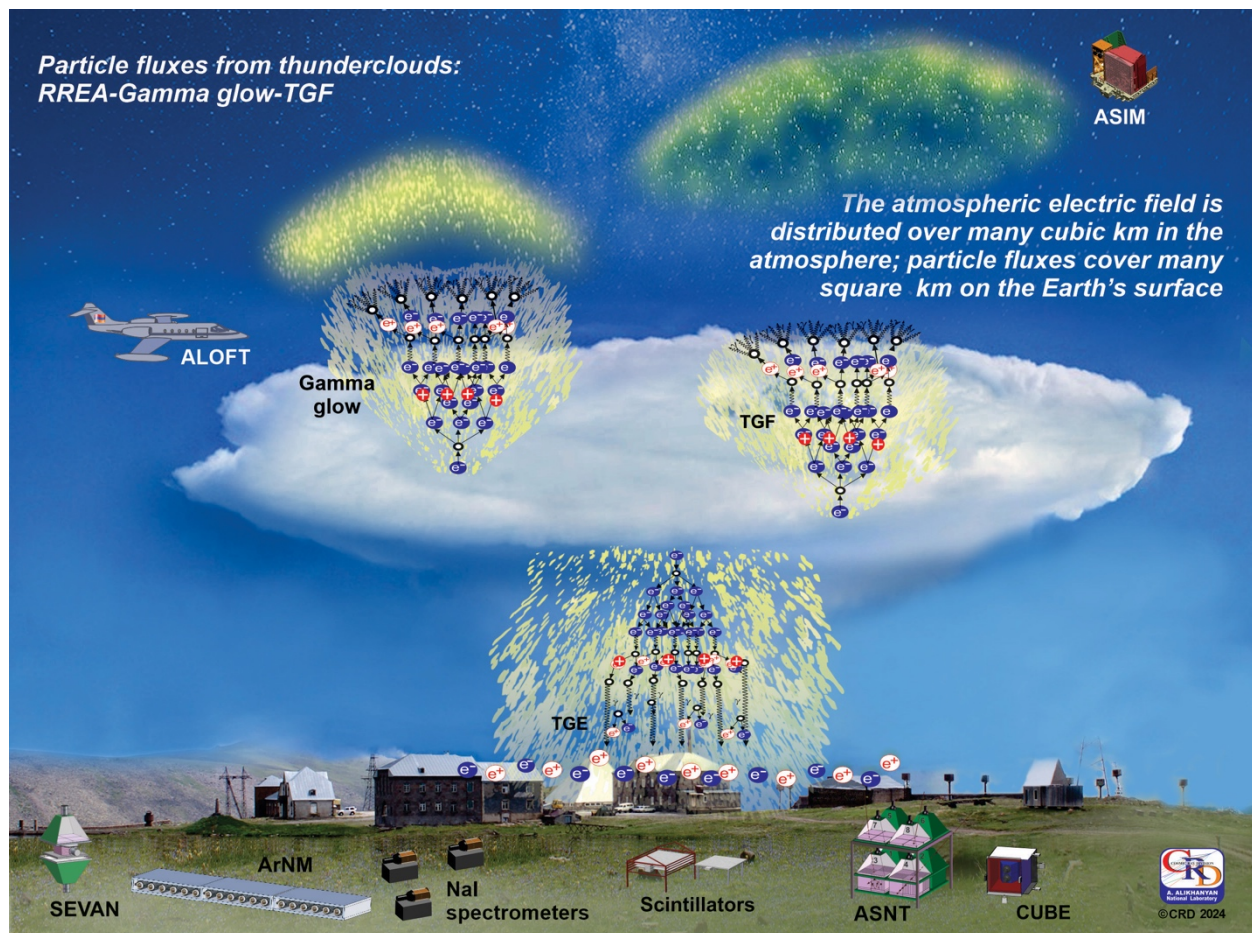


Figure 1. RREA originates extended particle fluxes in the upper and lower atmosphere.

4. Conclusion

Recognizing the same source for microsecond TGFs, minute-long gamma glows and TGEs marks a step towards accepting RREA as a universal physical process, which originates the enhanced particle fluxes in the lower and upper dipole. The subsequent terminology applies to the atmospheric fluxes of elementary particles produced during thunderstorms:

Terrestrial gamma-ray flashes (TGFs) are brief bursts of gamma radiation detected by orbiting gamma-ray observatories. They last for tens of microseconds, originate from thunderstorms at altitudes between 10 and 15 kilometers in equatorial regions, and are identified by gamma-ray observatories positioned 400 to 700 kilometers above the source.

TGEs (thunderstorm ground enhancements) refer to intense and prolonged particle fluxes observed on the Earth's surface, lasting up to several tens of minutes. These fluxes emerge from the same RREA process occurring within thunderclouds. However, the particle sources are in

close proximity to the detectors (50-100m), allowing for a detailed study of the energy spectra of electrons and gamma rays, as well as the corresponding charge structures of thunderclouds and the registration of fluxes from positrons and neutrons also arising from RREA.

Gamma glows are bursts of gamma radiation detected in the atmosphere by balloon or aircraft-based instruments. These events can last tens of seconds to several minutes and typically conclude with a lightning strike. The gamma-ray enhancements observed at the Earth's surface are also called gamma glows because, due to the high altitude of thunderclouds, they exclusively detect gamma rays and no other types of radiation particles.

Several research groups have also recently reported millisecond-long intense radiation from a source 1.5 km above the surface associated with lightning activity, referred to as "**Downward TGFs.**"

The primary mechanism driving TGFs, gamma glows, and TGEs is the **RREA**. This process originates intense electron-gamma-ray avalanches that can overpass the background radiation hundreds of times and accelerate seed electrons to 50-60 MeV energies. Simultaneous measurements of TGE electrons and gamma-rays confirmed RREA as a viable electron accelerator covering many km² areas on the Earth's surface.

However, a disconnect persists in the TGF research community, where the physical processes occurring in the upper atmosphere are often considered entirely different from those in the lower atmosphere. For instance, a recent TGF paper (Østgaard et al., 2024) states, "Two different hard-radiation phenomena are known to originate from thunderclouds: terrestrial gamma-ray flashes (TGFs) and gamma-ray glows." It is perplexing that such a distinction is made, given that the same physical mechanism—RREA—operates equally in the lower and upper atmospheres. This oversight neglects the vast wealth of TGE data (Chilingarian et al., 2024b). Nearly 1,000 TGEs have been observed on mountaintops across Eastern Europe, Japan, Russia, Germany, and Armenia. Combined with simulations, these observations have provided a detailed understanding of RREA development and cloud charge structures in the lower atmosphere.

Gamma glows, originating in upper atmospheric dipoles, exhibit different characteristics than TGEs. The high altitude, thinner air, and larger charges in the main positive layer of the upper atmosphere create distinct conditions for RREA development. Therefore, reserving the term "gamma glow" for particle fluxes observed in the upper atmosphere and "TGE" for particles observed on the Earth's surface is appropriate. Despite their different locations, these two phenomena—both powered by RREA—share similarities and would likely resemble each other if measured at the same distance from the source. Recent findings from the ALOFT mission support this conclusion (Marisaldi et al., 2024).

TGF was introduced in the 1990s to describe short bursts of gamma rays detected by satellites. TGF models propose that seed electrons originate not from cosmic rays but from streamers or lightning leaders. TGFs are rather an exotic phenomenon. Detecting microsecond-duration bursts of gamma rays by satellites positioned 400-700 kilometers from their source provides limited information for physical analysis compared to the wealth of data gathered from TGEs and gamma glows. Moreover, the spatial resolution of TGF measurements is inherently lower due to the great distance between the "accelerator" and the detector, as opposed to TGE and gamma glow detectors.

The term "**downward TGF**" is rather confusing. It refers to gamma bursts lasting around 200 milliseconds—significantly longer than traditional TGFs—detected on the Earth's surface. This phenomenon likely results from electron acceleration in the lower dipole, with properties distinct from the upper dipole. Efforts to connect “downward TGFs” with specific types of lightning remain inconclusive, and models proposing the creation of vast electron streams close to the Earth's surface seem implausible. Instead, particle bursts called “downward TGFs” can be explained by large-scale RREA processes in the electric fields of the lower atmosphere, similar to TGEs.

Broad scientific understanding requires incorporating the various experimental aspects of RREA phenomena that give rise to TGFs, TGEs, and gamma glows. Neglecting any part of this multidisciplinary research would lead to erroneous conclusions and narrow physical interpretations. I strongly advocate for a community-wide revision of the terms we use to describe these phenomena, providing a unified platform for all sides of the physical processes. This will help avoid further confusion in future research and improper citation policies in publications.

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