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RESEARCH ARTICLE

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Observation of a Downward Terrestrial Gamma-Ray Flash Associated With Dart Leaders of a Negative Cloud-To-Ground Lightning Flash

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Key Points:

- A downward terrestrial gamma-ray flash (TGF) was observed in association with a dart leader event
- The TGF occurred during the dart leader preceding the fifth of nine return strokes (RS) in the flash
- The peak current of the return stroke associated with the TGF was the highest among the nine RS

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract We report the observation of a downward terrestrial gamma-ray flash (TGF) during the dart-leader stage in a negative cloud-to-ground lightning flash. The observation was recorded by the Telescope Array Surface Detector, in conjunction with a Lightning Mapping Array, an interferometer (INTF), a fast antenna, and a high-speed camera. The return stroke was the fifth stroke of a negative cloud-to-ground lightning flash, which consisted of nine return strokes (RS) with three distinct ground-strike points. The peak current of the return stroke associated with the TGF was the highest among the nine RS. Its dart leader had the highest propagation speed in the flash, measuring at 2.33×10^7 m/s. The TGF was detected during the final stages of the dart leader, lasting 68 μs. The TGF emission was detected within a few microseconds of the return stroke, indicating that it persisted until the final stage of leader development. The total deposited energy of 1,352 MeV was recorded by the TASD; the fluence was estimated to be 8×10^{11} at the source, and the source altitude was estimated at 1.45 km above the ground. The observation of a downward TGF associated with a dart-leader stage supports the idea that the production of X-rays and downward TGFs are part of a continuum of energetic radiation related to lightning leaders.

Plain Language Summary Lightning flashes consist of one or more strokes. The first return stroke of a negative cloud-to-ground lightning flash is preceded by stepped leaders, which propagate through a non-ionized medium, while dart leaders advance through previously ionized channels. X-ray emissions and terrestrial gamma-ray flashes (TGFs) are observed to be produced by lightning during the leader stages. X-ray emissions have been observed during both the stepped and dart leader events, while downward TGFs have been primarily observed during stepped leader stages or with the first return stroke. In this paper, we report the observation of a downward TGF produced during the dart-leader stage in a negative cloud-to-ground lightning flash. This finding suggests a continuum in the production of X-rays and downward TGFs from lightning leaders.

1. Introduction

Terrestrial gamma-ray flashes (TGFs) are intense bursts of gamma rays with photon energies up to several tens of MeV (J. R. Dwyer & Smith, 2005). TGFs were first detected by the Burst and Transient Source Experiment in 1994 (Fishman et al., 1994). Later, TGFs were detected both by satellites (M. Briggs et al., 2010; M. S. Briggs et al., 2013; Gjesteland et al., 2012; Grefenstette et al., 2009; Marisaldi, Argan, et al., 2010; Marisaldi, Fuschino, et al., 2010; Neubert et al., 2020; Østgaard et al., 2019; Tavani et al., 2011; Smith et al., 2005) and ground-based observations (Abbasi et al., 2017, 2018, 2023; Belz et al., 2020; Chaffin et al., 2024; J. Dwyer et al., 2004, 2012; Hare et al., 2016; Tran et al., 2015; Wada et al., 2020, 2022).

TGF energy spectra derived from satellite observations are consistent with bremsstrahlung emissions inside thunderclouds (J. Dwyer et al., 2004; Smith et al., 2005). Therefore they are believed to be produced by relativistic runaway electron avalanches (RREAs), accelerated by strong electric fields inside thunderclouds (Carlson et al., 2007; Celestin et al., 2012; J. R. Dwyer, 2008; J. R. Dwyer & Smith, 2005; Gjesteland et al., 2010; Marisaldi, Argan, et al., 2010; Tavani et al., 2011; Xu et al., 2012). Due to the large number of charged particles at the source—estimated to range from 10^{16} to several $\times 10^{18}$—RREAs alone cannot fully explain the phenomenon. Two additional mechanisms have been proposed to better account for TGF production at the source: the relativistic feedback discharge model (L. P. Babich, 2005; A. V. Gurevich & Zybin, 2001; A. Gurevich et al., 1992; J. Dwyer, 2003; J. R. Dwyer, 2005, 2007, 2012) and the thermal runaway electron model or the lightning leader model (Carlson et al., 2009; Celestin et al., 2012; J. R. Dwyer, 2008; J. R. Dwyer & Cummer, 2013; A. Gurevich et al., 2007; Köhn & Ebert, 2015; Köhn et al., 2017, 2020; Xu et al., 2015).

X-ray emissions are another form of hard radiation, characterized by a lower energy spectrum—typically below 1 MeV. X-ray emission is observed in discrete bursts lasting less than 1 μs (J. R. Dwyer, 2004). The first reliable detection of X-rays associated with natural lightning strokes was reported by Moore et al. (2001); the emissions were detected 1–2 ms before the return stroke. Subsequently, X-ray emissions have been observed during the dart leader stage (Arabshahi et al., 2015; J. R. Dwyer et al., 2003, 2011; Saba et al., 2019; Saleh et al., 2009), as well as during the stepped leader stage (Biagi et al., 2010; J. R. Dwyer et al., 2005; Howard et al., 2008). Study of the spectral energy of X-ray emissions from stepped and dart leaders have indicated that the RREA mechanism cannot fully explain the low energies and high-flux X-ray emissions. Instead, the thermal runaway electron model

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was proposed to be responsible for the X-ray emissions during dart leader propagation (Celestin et al., 2015; J. R. Dwyer et al., 2004; Moss et al., 2006; Xu et al., 2014, 2017).

Observational and analytical research on X-rays examined X-ray generation by dart and stepped negative leaders, demonstrating radiation energies as high as 1–5 MeV (Contreras-Vidal et al., 2024; Hill et al., 2012; Mallick et al., 2012; Schaal et al., 2012)—blurring the boundary between downward TGFs and X-ray emissions. Furthermore, Telescope Array Surface Detector (TASD) measurements have identified downward TGFs (depositing energies between ~100 MeV to ~100 GeV) with weak to intermediate fluences $\left(\sim 10^{11} - 10^{15}\right)$ and short to extended durations ($< 10\ \mu s -$ up to $50\ \mu s$) (Abbasi et al., 2018, 2023, 2024; Belz et al., 2020), overlapping in fluence and duration with the upward TGFs reported in the ALOFT campaign (Bjørge-Engeland et al., 2024). These findings, together with evidence of X-ray emissions extending into the gamma-ray regime, suggest that TGFs span a broader range of fluences and timescales than previously recognized. This raises a key open question: are leader-produced X-rays and downward TGFs separate processes, or do they represent different manifestations of a continuous spectrum of high-energy radiation from lightning?

Despite overlapping energy spectra, the relationship between X-ray emissions and TGFs remains unclear, largely due to differences in their associations with parent lightning processes. While numerous studies have reported X-ray emissions linked to stepped and dart leaders, TGF observations show a more complex connection to their parent flashes. Most upward TGFs observed by satellites show that TGFs are typically produced during the initial phase of intra-cloud (IC) lightning flashes, coinciding with the upward propagation of leaders (Cummer et al., 2015; Lindanger et al., 2022; Lu et al., 2010; Østgaard et al., 2013; Shao et al., 2010; Stanley et al., 2006; Wu et al., 2025). On the other hand, some downward TGFs have been reported in association with cloud-to-ground RS (J. Dwyer et al., 2004; J. Dwyer et al., 2012; Tran et al., 2015; Ortberg et al., 2024), whereas other downward TGFs have been observed during the initial stages of stepped-leader development (Abbasi et al., 2017, 2018, 2023; Belz et al., 2020; Chaffin et al., 2024; Wada et al., 2020, 2022). Although there has been a single report of a TGF associated with a dart leader of a bipolar cloud-to-ground lightning flash (Kereszy et al., 2022), in this work we present the first observation of a TGF produced by a dart-leader stage of a negative cloud-to-ground lightning flash, as detected by the TASD.

The results of this work support the similarity between X-ray emissions and downward TGFs by showing that a TGF can be produced during the negative dart leader stage of a lightning flash. This result adds a new observational scenario to the existing paradigm. A brief introduction to the instruments used in the study is provided in Section 2. The observation and characterization of the TGF and its associated lightning strokes are presented in Section 3. The final section summarizes the observations and includes discussions of the role of the lightning leader model in the production mechanism of downward TGFs.

2. Experimental Setup

The observations were carried out at the TASD site using the same instruments and setup described in Belz et al. (2020), Abbasi et al. (2023, 2024), Kieu et al. (2024). The TASD stations detected the TGF by recording its energy deposition and waveforms, while complementary instruments characterized the associated lightning flash. These included 11 Lightning Mapping Array (LMA) stations, a broadband VHF Interferometer (INTF), a Fast Antenna (FA), a high-speed camera (v2012), and a slitless spectrograph. Full descriptions of these instruments are provided in the referenced publications; here we summarize the key features most relevant to TGF detection.

The TASD is a ground-based observatory located in the southwestern desert region of Utah, USA. It consists of 507 SDs, each with an area of 3 m^2 and 1.2 km away from each other, covering an area of 700 km^2, as shown by red diamonds in Figure 1. The TASD is triggered when three adjacent SDs each observe a signal greater than 3 Minimum Ionizing Particles (~ 150 FADC counts) within 8 μs. When a trigger occurs, signals from all individually triggered SDs within ±32 μs are recorded (Abu-Zayyad et al., 2012).

The LMA consists of 11 stations distributed over a 700 km^2 area encompassing the TASD site (blue circles in Figure 1). The LMA determines the three-dimensional locations of impulsive VHF radiation sources in successive 80 μs intervals (Rison et al., 1999; Thomas et al., 2004), and in this study was used to establish the plan locations of the TGF events. Complementing the LMA, a broadband VHF Interferometer (INTF) and a FA recorded the waveforms of associated lightning activity. The INTF operates in the 20–80 MHz range, sampling at 180 MHz with three receiving antennas, and provide sub-microsecond resolution measurements of the azimuth

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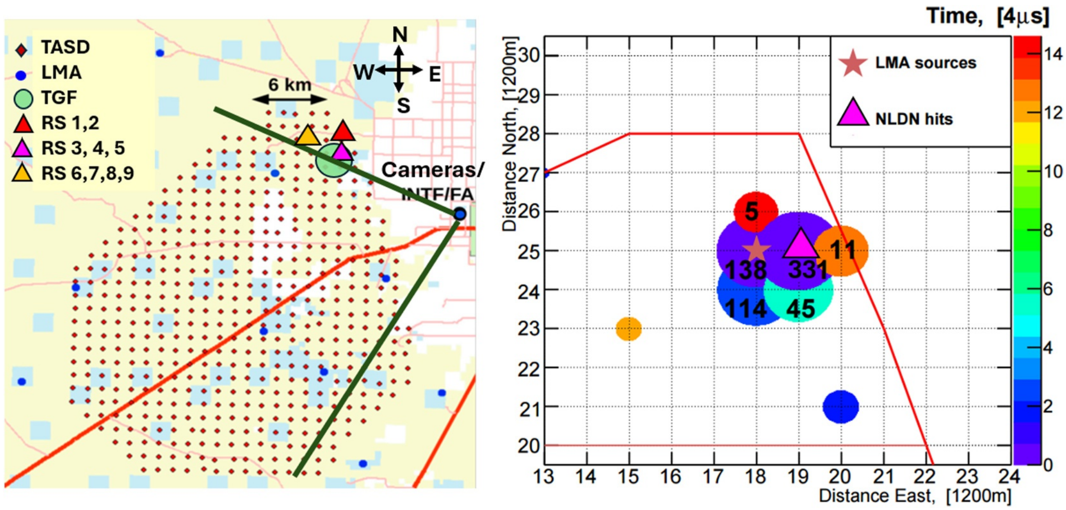

Figure 1. Locations of the detected terrestrial gamma-ray flash (TGF) and associated return strokes (RS). The left panel shows the Telescope Array Surface Detector (TASD) layout, with 507 stations marked by red diamonds. Blue circles indicate the locations of Lightning Mapping Array (LMA) stations. The high-speed camera, slitless spectrograph, Interferometer, and Fast Antenna are all housed in the same building. Two green lines depict the field of view of the high-speed camera, while two red lines mark the interstate roads in the southwestern desert of Utah. The bright green circle marks the location of the detected TGF. The red, pink, and yellow triangles represent the first, second, and third ground-strike points of the associated lightning flash, which included a total of nine RS. The right panel displays the TGF footprint detected by six adjacent TASD stations. Circle sizes are proportional to the logarithmic scale of the energy deposits, and the colors represent timing in 4-μs steps relative to the event trigger. Numbers on each detector indicate the energy deposits in Vertical Equivalent Muons (VEMs), with each VEM corresponding to 2.04 MeV. The brown star denotes the detected LMA source, and the pink triangle indicates the location of the National Lightning Detection Network hits.

and elevation arrival directions of VHF radiation (Belz et al., 2020). The FA, by contrast, measures electric field change (E-change) waveforms at 180 MHz, capturing low-frequency discharge sferics with high temporal resolution (Belz et al., 2020).

Optical images of lightning flashes were recorded by an optical system colocated with the INTF, consisting of a high-speed camera and a spectroscopic system. The high-speed camera, a monochrome Phantom v2012, operates at 40,000 frames per second (fps) with a time resolution of 25 μs. Its field of view is outlined by the green lines in Figure 1. The spectroscopic system consists of a grism (a combination of a diffraction grating and prism; 600 lines/mm) placed in front of another high-speed camera fitted with a 14-mm F/2.8 lens. This camera, a monochrome Phantom v711, records spectral images at 25,400 fps with a time resolution of 39.37 μs, covering a spectral range of 400–900 nm. The v711 operates at a lower frame rate than the v2012 to maintain the same field of view between the two systems. The high-speed camera v2012 was connected to the spectroscopic system. The two cameras were synchronized, and the v2012 triggered both whenever a change in luminosity was detected in its field of view (Kieu et al., 2025).

3. Observations and Characterization of TGFs and Associated Lightning Strokes

On 17 August 2024, a storm passed through the TASD site, producing nine TGFs between 16:00 and 18:00 UTC. One of these TGFs, detected at 16:18:45.019136 UTC, was temporally associated with a cloud-to-ground return stroke at 16:18:45.019200 UTC, which had a peak current estimated at −67.3 kA. According to the National Lightning Detection Network (NLDN), eight additional RS occurred within one second of this event at nearby locations, forming a flash with nine strokes in total with three ground strike points (Table 1). The TGF reported in this work occurred before the fifth return stroke. The FA recorded the electric field-change waveforms of all nine RS and an intra-cloud stroke (Figure S1 in Supporting Information S1). Their ground-strike points, plotted in Figure 1, show that strokes 1–2, 3–5, and 6–9 terminated at three distinct locations. The TGF location overlapped with the second ground-strike point where strokes 3, 4, and 5 struck.

Table 1
National Lightning Detection Network Detection of the Associated Lightning Flash

Stroke #	Leader type	Time	μsec	Latitude	Longitude	Peak Current (kA)	Type
1	Stepped Leader	16:18:44	744,222	39.4079	−112.8138	−31.2	CG
2	Dart Leader		773,483	39.4080	−112.8138	−18.7	CG
3	Stepped Leader		836,544	39.3885	−112.8164	−16.0	CG
4	Dart Leader		883,771	39.3887	−112.8166	−15.9	CG
5	Dart Leader	16:18:45	019,200	39.3893	−112.8186	−67.3	CGB
IC			020,408	39.4108	−112.8383	18.8	IC
6	Dart-Stepped Leader		112,690	39.3993	−112.8522	−9.0	CG
7	Dart Leader		256,885	39.4000	−112.8522	−48.8	CG
8	Dart Leader		319,633	39.4006	−112.8534	−41.9	CG
9	Dart Leader		374,976	39.3996	−112.8523	−11.6	CG

Note. A total of nine cloud-to-ground return strokes and one intra-cloud stroke were detected in this flash. The downward terrestrial gamma-ray flash was detected at 16:18:45.019,168 during the dart-leader stage of stroke 5. Return stroke 6 showed clear evidence of a horizontally propagating dart leader before turning downward as stepped leader along a new path to ground.

The TGF was detected by six adjacent TASDs with a combined energy deposition of 1,352 MeV, lasting for 68 μs. Both the TGF and the RS occurred in the northeastern part of the TASD array, as shown in Figure 1. The RS fell outside the field of view of the two high-speed cameras, resulting in missing optical images from the Phantom v2012, but the slitless spectrograph captured strokes 1–5. Its broader effective field of view, enhanced by the grism, enabled detection of these strokes, while strokes 6–9 were not imaged, likely due to the geometry of the third ground-strike point. The recorded images (Figure S2 in Supporting Information S1) show that strokes 1–2 shared a channel, while strokes 3–5 shared another.

Figure 2 shows the FA waveforms, interferometer (INTF) data, and optical signals for strokes 3–5, with a 1-ms zoom-in (panel A′) revealing that the TGF occurred during the dart-leader stage. Optical images confirm that all three strokes followed the same channel.

INTF data further characterize the leader development of strokes 3–5 (Figure 3). Stroke 3 developed through a stepped leader over 37.5 ms and terminated at an azimuth of 298°. Stroke 4 was preceded by a dart leader that propagated along the same channel and reached the ground at the same azimuth; its development lasted 0.3 ms, with a velocity of 1.52×10^7 m/s estimated from INTF data by fitting, derived from a linear fit to the elevation–time track. Stroke 5 was also preceded by a dart leader, which developed over 281 μs.

To precisely localize the TGF source and quantify the leader properties, cross-instrument timing analysis between the INTF, FA, and camera sources and the TGF location as observed by the TASD, as discussed in detail by Belz et al. (2020), determined a time shift of 36.8 ± 0.675 μs between the TASD and the colocated instruments. The TGF source location was constrained using the plan distance of the LMA sources together with the INTF elevation angle, allowing the source altitude above ground to be determined at the onset of the TGF (Belz et al., 2020). This analysis places the TGF source 13.9 km from the camera and yields a representative emission height of approximately 1.45 km above the four TASD detectors at the onset of the TGF. This altitude corresponds to the inferred location of the point-like TGF emission used in the fluence estimate. From the INTF elevation–time track, a linear fit to the dart-leader propagation yielded a velocity of 2.33×10^7 m/s. A summary of these observations and the characterization of the detected TGF is provided in Table 2.

Given the inferred source location and leader properties, gamma-rays above 100 keV were generated from a point-like source following the RREA spectrum and propagated through the atmosphere to the TASD instruments. As is standard in TGF fluence estimates, the RREA spectrum is assumed because the TASD observations cannot directly constrain the incident gamma-ray spectrum. Based on the shower footprint and source altitude, the gamma-ray radiation was assumed to be forward-beamed within a cone half-angle of $\sim 20°$. Using these simulations, the estimated fluence at the source was approximately 8×10^{11}. We define gamma-ray events operationally as lightning-related emissions detectable by the TASDs. GEANT4 simulations (e.g., Abbasi

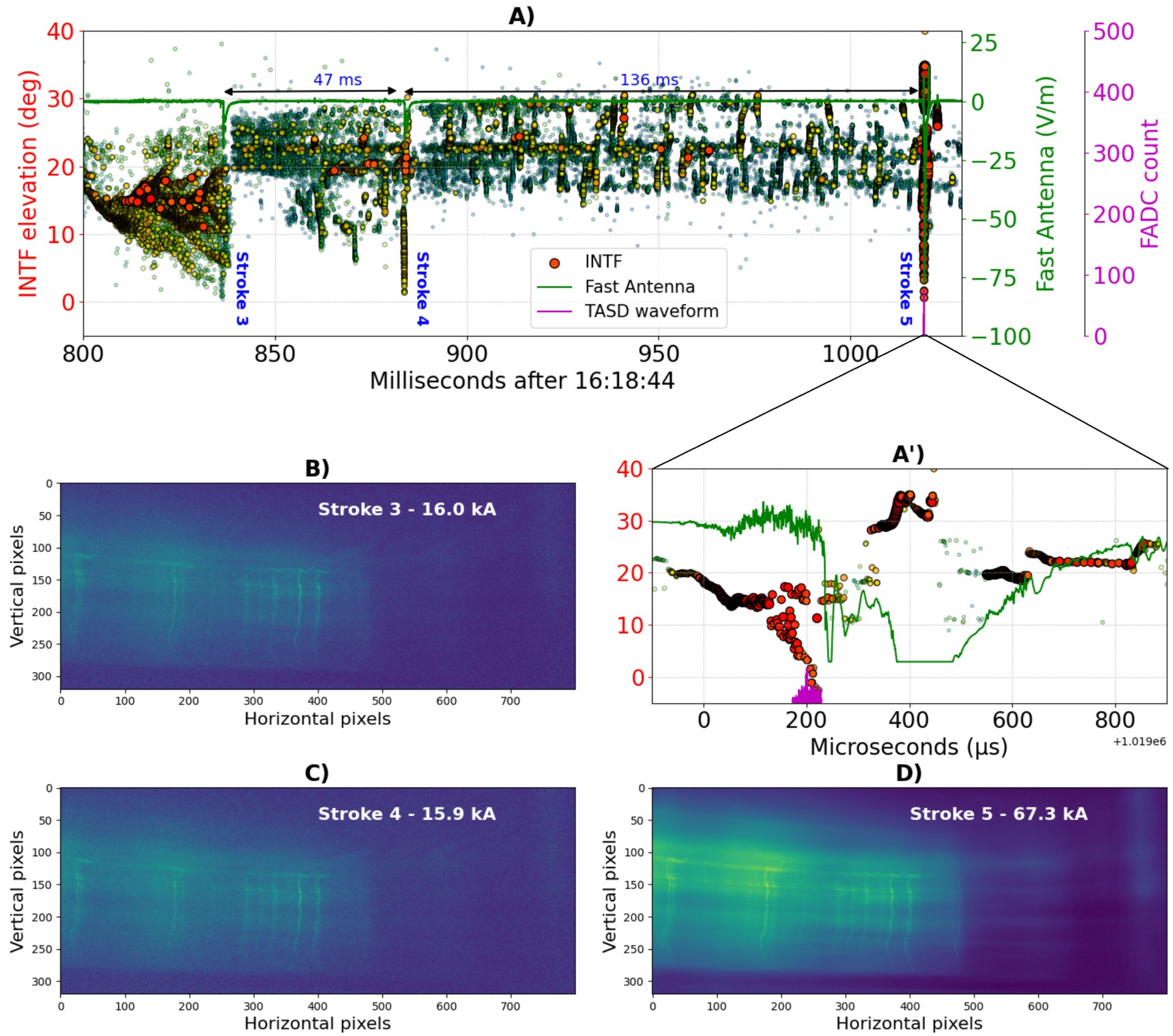

Figure 2. The E-change waveforms of strokes 3, 4, and 5 are plotted along with their interferometer (INTF) signals in panel (a) Green line signals depict the changing electric field recorded by the Fast Antenna, which is saturated at the return-stroke stage. Red circles represent INTF data, with their sizes and colors proportional to the power of the radio signal; those with lighter or non-red colors indicate low-power radio signals. Panel (a′) is a zoomed-in view of a 1-ms window around stroke 5. The magenta burst represents the terrestrial gamma-ray flash waveform detected by Telescope Array Surface Detector detector. Panels (b–d) display optical images captured by the slitless spectrograph, showing that the three strokes shared the same ground-strike point and leader channel. The horizontal and vertical axes in these images correspond to pixel indices and are numbered as shown in the figure.

et al., 2018) indicate that the TASD response is strongly suppressed for sub-multi MeV photons, rendering the array intrinsically blind to leader X-rays and sensitive only to events containing a high-energy gamma-ray component. Under this definition, all events with measurable multi-MeV photons are classified as TGFs.

Initial breakdown pulses (IBPs) are visible at the beginning of the flash prior to Stroke 1 (Figure S1 in Supporting Information S1), marking the onset of leader development; subsequent strokes do not exhibit IBPs. The stepped leader preceding stroke 3 developed over a long duration, whereas the dart leaders preceding strokes 4 and 5 developed more rapidly along pre-ionized channels. INTF observations show that stroke 3 followed a more complex path, while strokes 4 and 5 propagated along established channels with stronger signals. Additional strokes in the flash (Figures S3 and S4 in Supporting Information S1) show the same pattern: the absence of IBPs in the subsequent strokes and dart leader velocities exceeding 1.0×10^7 m/s. The dart-leader preceding stroke 5,

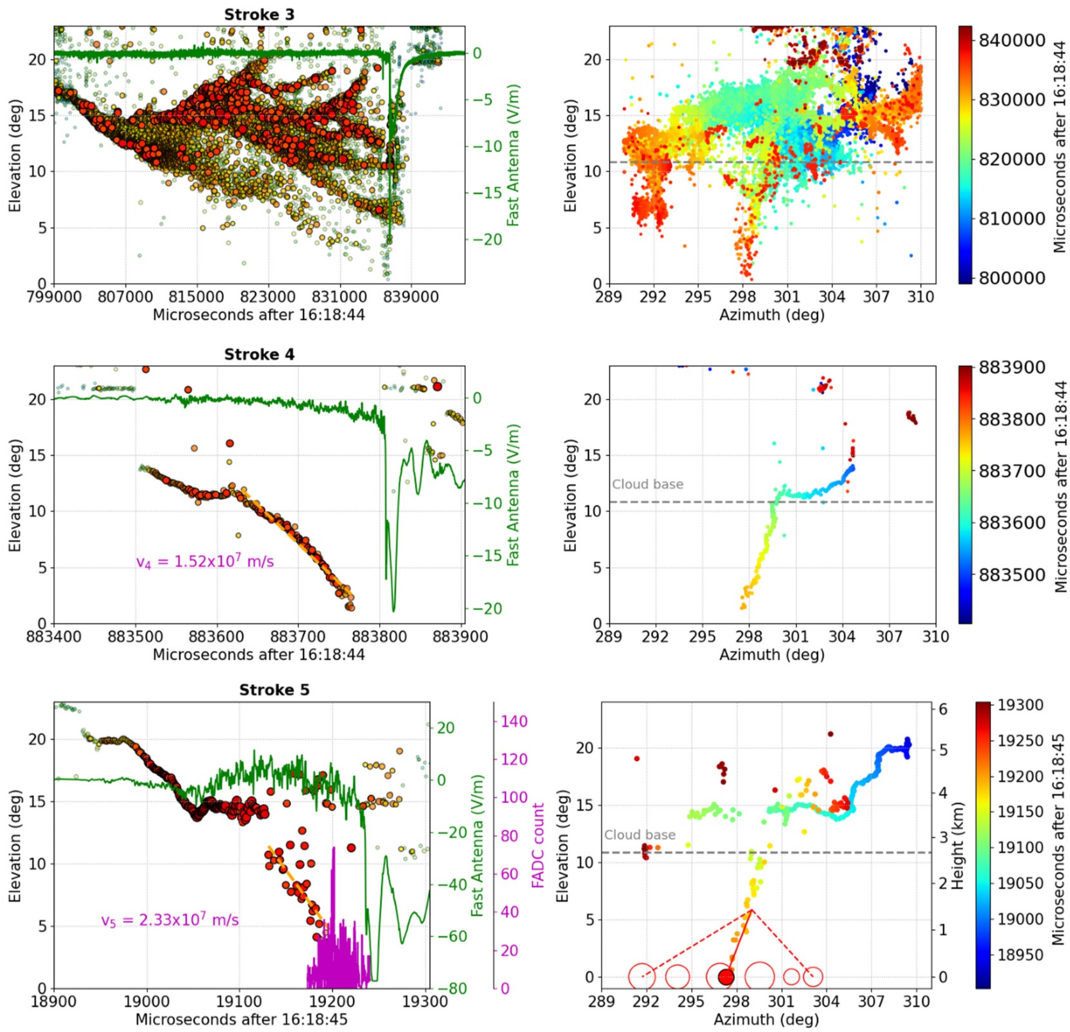

Figure 3. The right column shows interferometer (INTF) observations in the azimuth–elevation format, with colors indicating the timing of events from blue to red. The azimuth angle is defined such that 0° corresponds to North and increases clockwise. In the bottom-right panel, red lines extend from the inferred terrestrial gamma-ray flash (TGF) source location, with the source altitude above ground determined from the associated plan distance of the Lightning Mapping Array and the elevation angle of the INTF sources. This yields a representative emission height of approximately 1.45 km above the Telescope Array Surface Detector (TASD) detectors at the onset of the TGF. The triggered TASD detectors are marked by red open circles, with circle sizes representing the logarithmic scale of detected energy at each footprint station. The filled circles denote the energy-weighted centroid of the footprint. The left column shows the signals from the INTF, Fast Antenna (FA), and TASD. INTF elevations are shown by filled circles, with marker sizes and colors scaled to the radio-signal power, such that weaker signals appear smaller and lighter, and stronger signals appear larger and darker. Green lines indicate FA detections, and TGF waveforms are plotted in magenta in the bottom-left panel.

which produced the reported TGF, was the fastest observed in this sequence, with a speed of 2.33×10^7 m/s, exceeding the speeds of the other dart leaders in the flash.

4. Discussion and Conclusions

Sun et al. (2014) reported dart-leader speeds reaching up to 7.2×10^7 m/s, showing that exceptionally fast leader propagation can occur in later strokes, while Pu et al. (2019) linked dart leaders to chaotic pulse trains and potential energetic radiation. Other studies report similar ranges: for example, Campos et al. (2014) observed dart-leader speeds up to $\sim 1.9 \times 10^7$ m/s in natural lightning. Within this context, our measured leader speed of 2.33×10^7 m/s, representing the fastest leader within the flash, falls within this established range and is consistent with conditions favorable for energetic radiation production.

Table 2
Quantitative Values of the Lightning Mapping Array (LMA), National Lightning Detection Network (NLDN), and Telescope Array Surface Detector (TASD) Observations of the Lightning Flash Producing the Terrestrial Gamma-Ray Flash

Date	Time	μsec	LMA dBW	NLDN I_{pk}	TASD energy sum VEM/MeV	Number of TASD's
2024/08/17	16:18:44	836,544		−16.0 kA/CG		
		883,771		−15.9 kA/CG		
	16:18:45	018,408	9.9			
		018,502	2.3			
		018,786	11.8			
		019,136			644/1,352.6	6
		019,200		−67.3 kA/CG		
		019,565	35.7			

Note. The detection time of the LMA, NLDN, and TASD events are shown in chronological order. The LMA sensor recorded the VHF source powers. The NLDN detected the peak currents (I_{pk}) and classified them as either intra-cloud (IC) or cloud-to-ground (CG) flash. The TASD measured the total energy deposited in all adjacent surface detectors. The last column is the number of TASDs contributing to the total energy.

Building on these leader-speed observations, the characteristics of the leader-peak currents were next examined. Stroke 5 was distinguished by its high peak current of −67.3 kA, compared to −9 to −49 kA for the other strokes in the same flash. For context, Cruz et al. (2025) reported peak currents ranging from −4 to −57 kA, with a median of −13.5 kA, for subsequent strokes in a data set of 93 dart leaders observed using a high-speed video camera and the NLDN at the TASD. The −67.3 kA observed here lies above the typical range for subsequent RS. While peak current measurements primarily characterize the return stroke at ground level, such high values may reflect enhanced charge availability in the leader channel.

A second feature of the dart leader prior to stroke 5 is the presence of an air perturbation occurring before the TGF was detected. Here, "air perturbation" refers to localized changes in the ionization state and charge distribution that influence leader propagation. High-speed camera images showed that the three strokes shared the same channel path and ground contact point. However, INTF data revealed that, above the cloud base, the dart leaders of strokes 4 and 5 did not follow the same path. The dart leader of stroke 4 propagated along a single, well-defined path, while the dart leader of stroke 5 branched into three directions at a 15-degree elevation angle: one branch developed leftward, one proceeded downward; and another reversed direction. This branching behavior indicates non-uniform electric conditions ahead of the leader tip and is used here to infer the presence of an air perturbation. These observations indicate that although TGF production was associated with the dart leader below the cloud base, the combination of residual charge and this inferred air perturbation may explain why a TGF was produced.

To place the observed leader branching and inferred air perturbation in a theoretical context, we next consider lightning leader models that examine the role of air perturbations and preionization in runaway electron production. Lightning leader models studied by L. Babich et al. (2015), Köhn et al. (2020) suggest that the combination of air perturbations and preionization can significantly enhance the production of runaway electrons. In those models, preionization arises from corona streamers ahead of a stepped-leader tip, while in our case residual charges likely originated from previous RS. This combination of residual charge and air perturbation thus provides a plausible mechanism for TGF production in our observation.

To characterize the associated high-energy emission, our measurements show that the detected TGF occurred before the return stroke and lasted approximately 68 μs. The source altitude height was calculated to be 1.45 km above ground, with an estimated fluence of $\sim 8 \times 10^{11}$ at the source and a total deposited energy of 1,352 MeV in the TASDs. These values are consistent with previously reported downward TGFs (Abbasi et al., 2018, 2024), but the association with a negative dart leader is unprecedented. An expanded view of the TASD and FA observations shows that the TGF was detected to within 4 microseconds of the upward return stroke, placing the final detected energetic emission immediately prior to ground attachment and during the final stage of leader development.

Taken together, our observations are consistent with a possible association between the downward TGF in this event and a combination of high residual charge and complex air perturbations around the dart leader tip. These conditions may contribute to why TGFs are rarely observed in association with dart leaders. Our results show that it is possible for a TGF to be produced during the negative dart leader stage of a lightning flash, supporting the idea that downward TGFs and leader-associated X-rays may not be separate phenomena, but rather different expressions of a single lightning-driven process that produces a continuous range of high-energy radiation. In this respect, our findings complement recent studies that have emphasized spectral and phenomenological overlap between energetic X-ray bursts and short-duration TGFs (e.g., Zhang et al., 2025) and those that have documented leader-associated energetic radiation in lightning (Rakov & Kereszy, 2022). Unlike those works, which focus primarily on spectral characteristics and emission mechanisms, our case provides a leader-stage–resolved and dynamically constrained observation of a downward TGF during a negative dart leader, adding a new observational context to the continuum discussion.

This observation of a downward TGF associated with a dart-leader event advances our understanding of TGF production mechanisms by adding a new observational scenario complementing previous studies (Abbasi et al., 2024; Bjørge-Engeland et al., 2024; Zhang et al., 2025), establishing that TGFs can occur during the final stage of a dart leader in a multi-stroke negative cloud-to-ground flash, with simultaneous optical, and radio-frequency measurements. The multi-stroke nature of the flash further motivates comparison with detailed studies of dart leaders. While no concurrent X-ray measurements are available in this case, this observation addresses the question posed in the Introduction—whether leader X-rays and TGFs are separate phenomena or part of a unified radiation spectrum—by providing evidence consistent with a continuum interpretation. Our results are interpreted as supporting the latter interpretation, in which a shared origin rooted in lightning leader dynamics is plausible. To further test this continuum hypothesis, future observations would benefit from coordinated measurements combining high-time-resolution gamma-ray detectors; lightning mapping and interferometric networks; fast antennas; and high-speed optical imaging, particularly for multi-stroke cloud-to-ground flashes would help further investigate the connection between peak current, dart-leader charge dynamics, and TGF generation.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The data (processed data and source Python scripts used for figure generation) presented in this article are publicly available in the Open Science Framework repository (Abbasi, 2026).

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