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Published in:
Geophysical research letters

DOI:
10.1029/2022GL101597

ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2022GL101597

Ultra-Slow Discharges That Precede Lightning Initiation

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Key Points:

- The ultra-slowly propagating events travel at speeds at least an order of magnitude slower than the slowest positive leaders
- In one observed case, the slow propagation led directly into the formation of a lightning leader
- In most cases, these discharges are not connected with lightning initiation

Supporting Information:

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

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Citation:

Sterpka, C., Dwyer, J., Liu, N., Demers, N., Hare, B. M., Scholten, O., & ter Veen, S. (2022). Ultra-slow discharges that precede lightning initiation. *Geophysical Research Letters*, *49*, e2022GL101597. https://doi.org/10.1029/2022GL101597

Received 7 OCT 2022
Accepted 11 DEC 2022

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Abstract We report on ultra-slowly propagating discharge events with speeds in the range 1–13 km/s, much lower than any known lightning process. The propagation speeds of these discharges are orders of magnitude slower than leader or streamer speeds, but faster than the ion drift speed. For one particular event, a lightning leader forms about 40 ms later within 50 m of the discharge, likely within the same high field region. A second slow event forms 9 ms prior to the initiation, and leads into the negative leader. Most slow events appear to not be directly involved with lightning initiation. This suggests that the classic streamer cascade model of initiation is not always a definitive process. In this work we describe these discharge events displaying unique behavior, their relation to common lightning discharges, and their implications for lightning initiation.

Plain Language Summary While lightning is generally a very fast process, here we report on ultra-slow discharges which may be a new and unexpected method of lightning initiation. These discharges travel at uncharacteristically low speeds and are observed in conjunction with lightning initiation in two cases, while in three different cases they are not. This indicates that these events are also evidence of failed lightning leader formation, which complicates the current understanding of how lightning initiates. Additionally, the velocity of these events is slow enough that in principle the propagation can be observed by the unaided eye - challenging the colloquial notion of "fast as lightning."

1. Introduction

Lightning is generally a very fast process, with each discharge having a range of associated speeds. The slowest reported speeds are positive leaders, which are commonly reported in the range of $1.6–3 \times 10^4$ m/s, with an average velocity of about 2×10^4 m/s (van der Velde & Montanyà, 2013) (with an exception for one esoteric reference to rocket lightning, which travels "about as fast as a rocket" [Everett, 1903]). In 2D video observations, the speeds reported are possibly as low as 10 km/s (Kong et al., 2008). Negative leaders, which are a branched lightning process that expands outward as it approaches ground or another positively charged region, propagate at speeds between $1–6 \times 10^5$ m/s (Hill et al., 2011). Streamers, which are a cold-plasma phenomena underpinning many discharge processes in lightning including both initiation and propagation, have been shown to possibly have speeds as low as 10^5 m/s just above the critical field for streamer formation (Dwyer & Uman, 2014; Koile et al., 2020; Liu & Dwyer, 2013), but have been observed as fast as 1×10^7 m/s in sprites (McHarg et al., 2007; Phelps & Griffiths, 1976). In typical lightning initiation processes, however, it is has been shown that positive streamers grow in VHF at 4.8×10^6 m/s (C. Sterpka et al., 2021). Anvil crawlers, also known as spider lightning, are mistaken for slowly propagating leaders where the propagation can be observed by eye. However, this is only due to the spatial extent in which they cover, their travel speeds are between $2–4 \times 10^5$ m/s (Mazur et al., 1998; Peterson et al., 2021).

In this work, imaging for all figures is performed with the Time Resolved Interferometric 3D (TRI-D) imager, which provides location, intensity, and polarization of sources (Scholten et al., 2021a). This is possible in part due to LOFAR's thousands of VHF (30–80 MHz) dual-polarized antenna pairs, of which typically between 150 and 200 are selected to allow for extraordinary sensitivity through interferometric beamforming. This enables the detection of lightning features with meter-scale precision and intensities that are below the level of galactic background (Hare et al., 2018; Scholten et al., 2021a; C. Sterpka et al., 2021). While the location uncertainties due to the galactic and thermal background are typically in the centimeter scale, Monte Carlo simulations have shown that imaging through the TRI-D typically achieves 1–10 m accuracy (Scholten et al., 2022). This is mainly dependent on the contributions from other sources at the precise time that the source in question is active

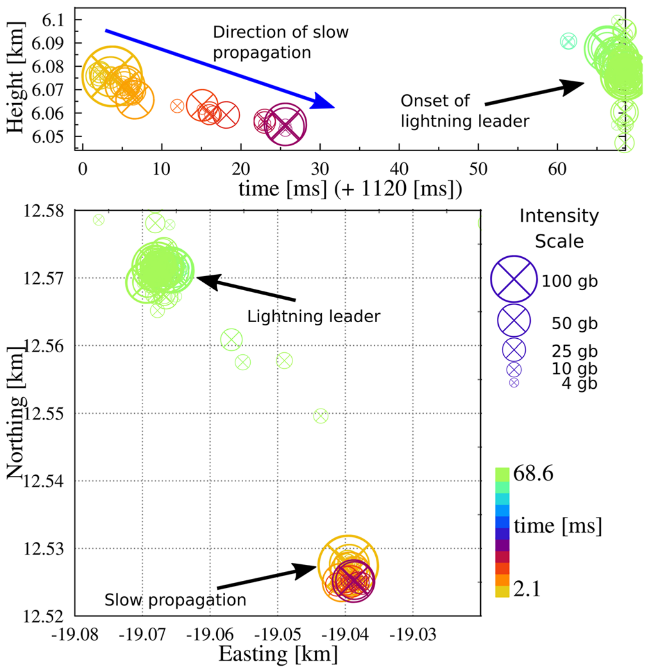

Figure 1. This figure displays the first ultra-slow propagation from the 20B-10 flash and the lightning leader that follows 40 ms after the cessation via a wagon-wheel TRI-D plot. The slow propagation and lightning leader sources are labeled with arrows in both the altitude versus time (top) and ground projection (bottom). The color indicates the relative timing, and the size indicates relative intensity (intensity scale on right). The initial development of the slow propagation is followed by the onset of the lightning leader in green. Note that overlap of the sources in the ground projection indicates the close proximity of the separate discharges.

(Scholten et al., 2022). The intensity units used within this work are orders of the galactic background (gb), and they represent the normalized noise level for individual antennas (Scholten et al., 2021a; C. Sterpka et al., 2021). In this paper we will present four ultra-slowly propagating discharge events imaged by the LOFAR radio telescope.

2. Results

The first slow propagation event was discovered in close proximity to a flash that took place on 27 June 2020 at about 14:51 UTC, denoted as flash 20B-10. Imaging was performed with 183 antenna pairs and sources were found to develop about 65 ms before the initiation of a negative lightning leader (Figure 1) and about 50 m southeast from the initiation location. The event took place 19 km west, 12 km north, and at an altitude of about 6 km from the LOFAR core. On the top left of the figure, the altitude versus time for the slow propagation is displayed in a wagon wheel style TRI-D plot. The top right of the same plot shows the initial development of the lightning leader, about 65 ms after the start of the slow propagation. The size of each wagon wheel indicates the relative VHF intensity. Note that the intensity of the slow propagation is similar to the initial intensity of the first few sources of the lightning leader. As the slow propagation moves in the same direction as the negative leader, this indicates that its polarity must also be negative.

The second figure displays quadratic fits for the ultra-slow propagation via a least squares regression. The fits exclude sources that are more than 2.0 standard deviations from the central curve along each axis (omitted sources are indicated by a red "x"), and the intensity is cut to 2.0 gb; these cuts ensure sources which are artifacts of sidebeams and/or different distributions are excluded from the fit. The points indicate the source locations along the Easting (top panel), Northing (second panel from top), and altitude axes (third panel from top). The bottom panel provides a histogram of the spread density and a normal distribution with a 1.1 m standard deviation. The distribution indicates the source distances from the 3D position vector, which has been calculated from the fits to the source coordinates versus time for each of the axes. The fits reveal that the discharge begins with a speed of about 1.9 km/s and decelerates to a speed of about 0.5 km/s, with an overall acceleration of -91 km/s^2. Initially, there are several clusters of sources which form less than 1 ms apart (indicated by the purple, orange, and red source groupings on the top panel of Figure 1), then as the discharge progresses there are several sources which develop either individually or with only one or two adjacent sources to form a cluster. This continues until the cessation of the discharge 25 ms later. The propagation moves downward about 21 m, with a slight lateral velocity on both the North and East axes with displacements of 1.8 and 1.1 m respectively.

Figure 3 shows a zoom in of the negative leader, which is of significant interest as the initiation also begins with an ultra-slowly propagating discharge. Note that from 66 to 68.5 ms the propagation is linear with a speed of about 1.5×10^3 m/s; this abruptly changes to 1.2×10^6 m/s slightly after 68.5 ms with the onset of the lightning leader. Even more surprising, the located sources in the first 6 ms prior to the discharge displayed in Figure 3 are stationary within the margin of error of LOFAR (see Figure S1 in Supporting Information S1). They are separated from each other by only about 0.25–0.5 m for an average speed of only about 300 ± 200 m/s.

A third slow propagation event (Figure S3) was also found within the same data set and appears to be unconnected with local lightning activity. Sources developed 18 km west, 8 km north, and at an altitude of about 10 km from the LOFAR core. The discharge has a linear speed of about 1.0 km/s. Initially, there are only a few sources that develop, with the largest burst of activity forming 15 ms after the discharge starts. The closest lightning activity to this event is about 700 ms before the slow propagation starts and 2.5 km from the discharge, both lower in altitude and south. What is particularly surprising about this discharge is that the propagation is not along the vertical axis, which is the usual electric field direction. While both negative and positive leaders are observed to grow horizontally in thunderstorms, the trajectory of the slow propagation is mainly along the north-south axis from the inception point, which is not typical of lightning discharges (Wu et al., 2015; Yuan et al., 2019).

The fourth observed slow propagation event (Figure S4 in Supporting Information S1) was found in close proximity to a flash that took place on 18 June (colloquially known as The Netherlands Apocalypse Storm) at 17:46 UTC in 2021, denoted flash 21C-1. The event was imaged with 180 antenna pairs and occurred 20 km west, 16 km South, and at an altitude of about 11 km from the LOFAR core. The discharge took place 800 ms before the nearest lightning event. This lightning discharge formed an intensely radiating negative leader (IRNL) (Scholten et al., 2021b), about 150 m to the East. The slow discharge began with a slightly higher speed of about 12.5 km/s and quickly decelerated to a speed of about 1.7 km/s with an overall rate of change in velocity of $-1{,}158$ km/s^2. Since the propagation is in the upward direction, this event also must be a negative polarity event.

3. Discussion

The initial speeds of these discharges are typically of the order of 1×10^4 m/s, but in some cases deceleration brings the speeds possibly as low as 100 m/s. For some of the ultra-slowly propagating discharges, the standard deviation of the trajectories is of the order of 1 m, indicating that the diameter of the channels is of the order of our resolution or less. These events have intermittent bursts where the average location of each burst collectively forms an overall motion that in some cases can be fit with a decelerating quadratic trajectory; although for the discharge which initiates lightning, this was not the case.

While the ultra-slow discharges typically decelerate, the trajectory that preceded lightning had three distinct stages. Initially, the sources effectively remained in a fixed location over the first 6 ms (see Figure S1 in Supporting Information S1). This was followed by an abrupt transition to a constant velocity of about 1.5×10^3 before another abrupt change in velocity to 1.2×10^6 m/s as the leader forms. The final two stages are analogous to results of previous observations of lightning initiation events (C. Sterpka et al., 2021). However, the major differences are the ultra-slow speed, the intensity profile of the initiating event remaining relativity constant throughout the trajectory, and that the constituent bursts are initially sparse, but then the density of sources increases.

As mentioned previously, since these events are likely within the same high field region of the thunderstorm and lead into an initiation event, this adds potential complications to the classic Griffiths and Phelps model (Griffiths & Phelps, 1976); if streamers form on hydrometeors within the same high field, why is it that in one location 50 m from the initiation a slow propagation forms without lightning initiation, however at the exact location it leads into leader formation? One would expect that the hydrometeor density and fields within this region should be of similar magnitude, otherwise the initiation would not take place. While LOFAR measurements are currently limited to a passband of 30–80 MHz, with peak sensitivity at 58 MHz, this range is the expected sensitivity for streamer processes (Hare et al., 2018; Lyu et al., 2016). Additionally, previous studies (Rison et al., 2016; Tilles et al., 2019) have reported that lightning initiation begins with fast breakdown, but if lightning can initiate with an ultra-slow discharge or possibly even stationary discharge, how would this modify the understanding of virgin air breakdown? Typically observed streamer cascade initiation events have been shown to initiate with velocities between 2 and 4 orders of magnitude higher than the ultra-slow propagations (Rison et al., 2016; C. Sterpka et al., 2021; Tilles et al., 2019). This implies that if the discharges are related to the classic Griffiths and Phelps streamer cascade processes and they more often fail to trigger lightning than successfully initiate lightning, then this model cannot be a straightforward process in all cases (Attanasio et al., 2019; Griffiths & Phelps, 1976). Or, to be more explicit, simply having a field above the level required for breakdown and a high enough hydrometeor density to enable the formation of streamers may be necessary, but not sufficient conditions for the formation of a lightning leader (Dwyer & Uman, 2014). Lastly, as the slow propagation that forms in conjunction with the lightning leader leads into the initiation, what is the cause of the spontaneous transition?

Since these ultra-slowly propagating discharges are not always found in conjunction with an initiation event, they could also be connected with failed leader initiation (Kolmašová et al., 2020; Shao et al., 1995). Every other time that lightning initiation has been observed it's been a fast process, but these events do not necessitate the formation of lightning. The temptation is to think that the E-fields are below the breakdown threshold, however it is not clear that would resolve the issue as leaders have been observed in low electric fields. Additionally, no leaders have been observed this slow, and certainly nothing that travels this slow for up to a hundred meters and for up to 70 ms (Hill et al., 2011; Kong et al., 2008; van der Velde & Montanyà, 2013). One final note is that the

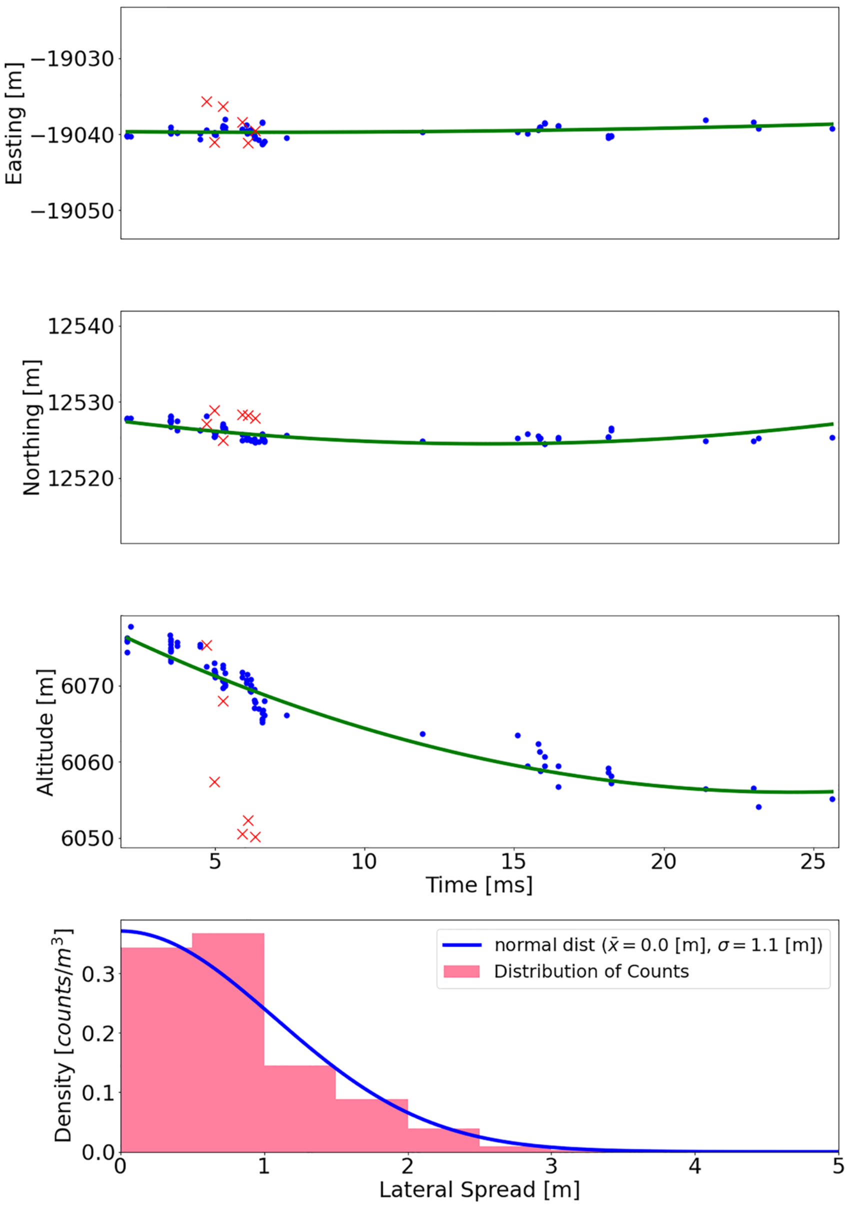

Figure 2. First slow propagation, approximately 65 ms before the initiation of flash 20B-10. Top panel shows the Easting versus time, middle top shows Northing versus time, middle bottom shows altitude versus time, and the bottom panel provides the spread density from the fit to the 3D position vector and corresponding normal probability distribution. The overall acceleration is 91 km/s^2 with $v_0 = 1.9$ km/s, $v_f = 0.5$ km/s. Sources outside two standard deviations along each axis are excluded from the fit and are indicated by a red "x." The black arrow denotes a burst that propagates away from the main trajectory.

number of clusters are decreasing for the ultra-slow events that do not initiate lightning, but for the event that does initiate lightning the number of clusters increases with time. The natural inclination is to think that this would be indicative of an increase in hydrometeor density within the initiation region, but the issue with this conjecture is that this would mean that the density of hydrometeors would be changing on millisecond timescales, which seems highly unlikely.

What is surprising about these events in addition to their ultra-slow speeds is that there are gaps in the detected VHF activity during the event that can last from fractions of a millisecond to tens of milliseconds. Additionally, our data shows that sometimes bursts form propagating features that are nearly perpendicular to the trajectory (see, e.g., the sources indicated by the black arrow in Figure 2), similar to previously discovered positive leader

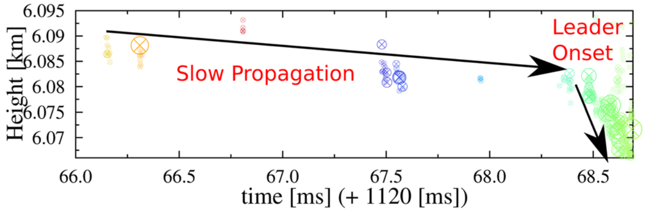

Figure 3. Zoom of initialization of leader initiation from the 20B-10 flash displayed in Figure 2. Note that discharge begins with ultra-slow propagation on left prior to the formation of the lightning leader on right. Since we are fitting the overall motion of the ultra-slow propagation, the weak sources that form the vertical lines are considered part of a different distribution and are ignored. Additionally, note that only the final 2.5 ms of the slow propagation are shown.

needles (Hare et al., 2019). Optical measurements of positive leader velocities have shown that they may travel as slow as 1.0×10^4 m/s (Hare et al., 2019; van der Velde & Montanyà, 2013). These connections are interpreted as only analogous features, as the overall propagation follows the expected upward trajectory of a negative leader for this altitude. This does however lead to the question of whether the structure and/or the frequency of the bursts are indicative of successful versus unsuccessful lightning initiation events. It is not expected that the ultra-slow discharges contain a hot leader channel; this is resultant from the fact that the discharges are the only detected VHF emission in several of the cases, also, one is observed prior to the formation of a lightning leader. Future measurements can examine if these events also involve optical or low-frequency emissions, and whether they are simply a collection of related bursts or if there is a continuous discharge that propagates along the trajectory.

One of the explanations that has been proposed and rejected is that this trajectory is somehow related to the ion drift velocity. This hypothesis was implausible, due to the fact that the ion drift speed at 6 km altitude is expected to only be about 600 m/s, so even the slowest event reported here would already exceed this by a factor of 2 (Dwyer & Uman, 2014).

4. Conclusions

Within this work we highlight the features of these ultra-slowly propagating discharges through true 3D VHF beamforming that is only possible with the sensitivity of the LOFAR array. Future work will need to address the following questions.

1. Are the ultra-slowly propagating discharge events a common or uncommon method of lightning initiation and/or failed initiation?
2. Do the bursts form disorganized clusters or do they share features of streamer or leader discharges? Consequently, do the burst structures and/or frequency suggest whether the propagation leads to initiation versus failed initiation?
3. Are there are associated environmental differences between the events that fail to initiate lightning versus those that succeed?
4. Most importantly, what are the physical processes that produces their ultra-slow speeds and corresponding implications for the Griffiths and Phelps model, given their role in initiation?

We have identified discharges that are remarkable both in their slow speeds and frequency in occurrence within LOFAR data. While only four events are described within this work, seven have been observed within three different data sets. The events presented here suggest a new form of lightning initiation and/or failed initiation characterized by velocities orders of magnitude slower than any known discharge process. This is supported by the fact that in at least one case the slow discharge leads directly into the formation of a lightning leader, although most of the observed propagations do not lead to lightning initiation. Given these facts, it is essential that further study address the outstanding questions to find their proper role in both initiation and failed initiation as well as the underlying physics behind their ultra-slow propagation speeds.

Data Availability Statement

Figures in this work were created with the Matplotlib Python package (Caswell et al., 2019). Processed data are hosted on zenodo.org (C. F. Sterpka et al., 2022). Raw data are located on the LOFAR Long Term Archive and can be downloaded after setting up a LOFAR LTA account and through following the instructions for "Staging Transient Buffer Board Data" (Asabere, 2020) using the wget software package as follows: wget –no-check-certificate https://lofar-download.grid.surfsara.nl/lofigrid/SRMFifoGet.py?surl=srm://srm.grid.sara.nl/pnfs/grid.sara.nl/data/lofar/ops/TBB/lightning/L786655_D20200627T145100.178Z_"station"_R000_tbb.h5 and "station" is replaced with one of the names of the LOFAR stations: CS001, CS002, CS003, 258 CS004, CS005, CS006, CS007, CS011, CS013, CS017, CS021, CS024, CS026, CS028, CS030, CS031, CS032, CS101, CS103,

RS106, CS201, RS205, RS208, RS210, CS301, CS302, RS305, RS306, RS307, RS310, CS401, RS406, RS407, RS409, CS501, RS503, RS508, or RS509.

Acknowledgments

Computations were performed on Marvin, a Cray CS500 supercomputer at UNH supported by the NSF MRI program under grant AGS-1919310. This research was supported in part through the University of New Hampshire AFOSR Grants FA9550-16-1-0396 and FA9550-18-1-0358 and by NWO VI.VENI.192.071.

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