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Toward a better understanding of negative lightning stepped leaders

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A R T I C L E I N F O

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A B S T R A C T

Negative lightning leaders observed at very close (within a few kilometers) distances often exhibit heavy branching with many active tips forming a network-like structure with a descending multi-tip "ionization front" whose transverse dimensions are of the order of hundreds of meters. The presence of such front makes the lightning attachment process more complex than usually assumed. Negative leader branches extend in a step-like manner, with each step necessarily generating a traveling wave moving positive charge from the branch tip up along the channel, like a mini return stroke. The leader stepping process has a number of generally unrecognized consequences. Specifically, a stepped-leader branch tip can collide with the lateral surface of an adjacent branch (usually at an angle of about 90°). Further, the step-related positive-charge waves propagating from the tip up along the channel can reactivate decayed negative branches at higher altitudes. Overall, a heavily-branched negative stepped leader creates a highly-structured and rapidly-changing electric field pattern inside and in the vicinity of the volume it occupies, which causes complex interactions between the branches.

1. Introduction

There has been significant progress lately in studying lightning leaders (including their stepping process) (e.g., Petersen and Beasley (2013) [1], Qi et al. (2016) [2], Kostinskiy et al. (2018) [3], Syssoev et al. (2020) [4], Khounate et al. (2021) [5]) and their attachment to grounded objects (e.g., Visacro et al. (2017) [6], Rakov and Tran (2019) [7], Saba et al. (2017) [8], Jiang et al. (2021) [9]). However, some aspects of leader propagation and attachment remain unclear. In this paper, we will focus on some less known and even unexpected features of downward negative stepped leaders, such as collisions of leader branches (Ding et al., 2021 [10]) and transients associated with reactivation of decayed branches at higher altitudes (Stolzenburg et al., 2015 [12]; Ding et al., 2020 [11]). We suggest that both these features are related to (facilitated by) the leader stepping process, although Stolzenburg et al. (2015) [12] offered a different theory. The paper is based on (is an extended version of) the Keynote Speech given by the authors at the GROUND 2020/21 & 9th LPE in Belo Horizonte, Brazil.

Negative lightning leaders developing in virgin air are necessarily stepped (extend intermittently). They tend to branch more when they approach the ground (e.g., Qi et al. (2016) [2]; Ding et al. (2021) [10]). Several active tips can exist at the lower extremity of each extending branch or sub-branch of negative leader. Petersen & Beasley (2013) [1], Hill et al. (2011) [13], and Qi et al. (2016) [2], who used high-speed video cameras with interframe intervals of 100, 3.33, and up to 25 μs, respectively, for imaging natural negative lightning within 1 km or so of the recording station, observed space stems/leaders several meters below or on the side of the primary leader tip that connected to the primary leader channel causing its stepwise extension. Jiang et al. (2017) [14], using a high-speed video camera with 5.6 μs interframe interval, observed 2 negative stepped leaders at distances of 410 and 1080 m from the camera. They found that leader branching was due to the connection of multiple space leaders to the same channel branch tip (first reported by Tran et al. (2014, Fig. 2) [15]), either simultaneously or sequentially. Alternating stepping in branches originating from the same branching point was observed, with the occurrence of step in one branch causing luminosity reduction in the other branches.

It is known that streamers, which are cold and poorly conducting plasma formations, can interact with each other in a number of ways, including collisions. Nijdam (2011) [16] presented experimental evidence of positive laboratory streamers making connection to the lateral surface of other positive streamers. He referred to such streamer collisions as "reconnections" and suggested that they were caused by electrostatic attraction of a later streamer to the remnants of an earlier streamer which already has crossed the gap and changed polarity. Similar collisions were reported for sprites, which involve large-scale (up to tens of kilometers) downward extending streamer formations in space between the ionosphere and cloud tops (Cummer et al. (2006)

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[17]; Montanyà et al. (2010) [18]; Stenbaek-Nielsen et al. (2013) [19]; McHarg et al. (2019) [20]; Contreras-Vidal et al. (2021) [21]). Note that, in contrast to streamers, leaders have a hot and highly conducting core and that the mechanism of leader branch collision may be different from that of streamers.

Stolzenburg et al. (2015) [12] presented a very thorough and detailed characterization of the transient luminous features associated with brief reactivation of decayed leader branches and suggested a possible mechanism of their occurrence based on electrostatic considerations. According to their theory, a decayed branch left behind at a higher altitude by a descending leader at a later time is at a higher (in absolute value) potential than the main channel whose potential becomes lower as it approaches the ground. This mechanism does not involve any traveling waves prior to the transient. In this paper, we present a different mechanism of reactivation of decayed leader branches, the one associated with leader stepping. It is possible, and even likely, that both our mechanism and that suggested by Stolzenburg et al. (2015) are at work as the negative stepped leader approaches ground.

The structure of the paper is as follows. Instrumentation is described in Section 2, and a detailed description of the basic negative leader stepping mechanism is given in Section 3. The latter is necessary for understanding the newly observed phenomena presented and discussed in Section 4. Summary is given in Section 5.

2. Instrumentation

All the data presented in this paper were obtained at the Lightning Observatory in Gainesville (LOG), Florida, with three high-speed video cameras, Megaspeed HHC-X2 (visible range; 0.4–0.8 μm), Phantom V310 (visible range; 0.4–0.8 μm), and FLIR X6900sc (medium-to-far infrared range; 3.0–5.0 μm). The MegaSpeed camera was coupled with a fisheye lens providing a very large field of view and was operated at 1000 fps with 1-ms exposure time and no dead time. Its resolution was 600 × 832 pixels. The Phantom camera had resolution of 288 × 512 pixels and was operated at 20,000 fps with 47.39-μs exposure time and 2.61-μs dead time. The FLIR camera was operated at 1004 fps with 0.8-ms exposure time and 196-μs dead time. Its resolution was 640 × 512 pixels. The brightness of IR images reasonably represents the gas temperature of the discharge channel. The cameras were set to trigger on electric field changes produced by close lightning discharges (within about 6 km of LOG). Schematic overview and photographs of LOG are shown in Fig. 1. More detailed information on LOG and its instrumentation can be found in the review papers by Rakov et al. (2014, 2018) [22] and [23].

NLDN (U.S. National Lightning Detection Network) data were used to determine the distances to lightning channels. All the length and speed estimates presented in this paper are 2D.

3. Negative leader stepping mechanism

The first reasonably complete and clear description (including

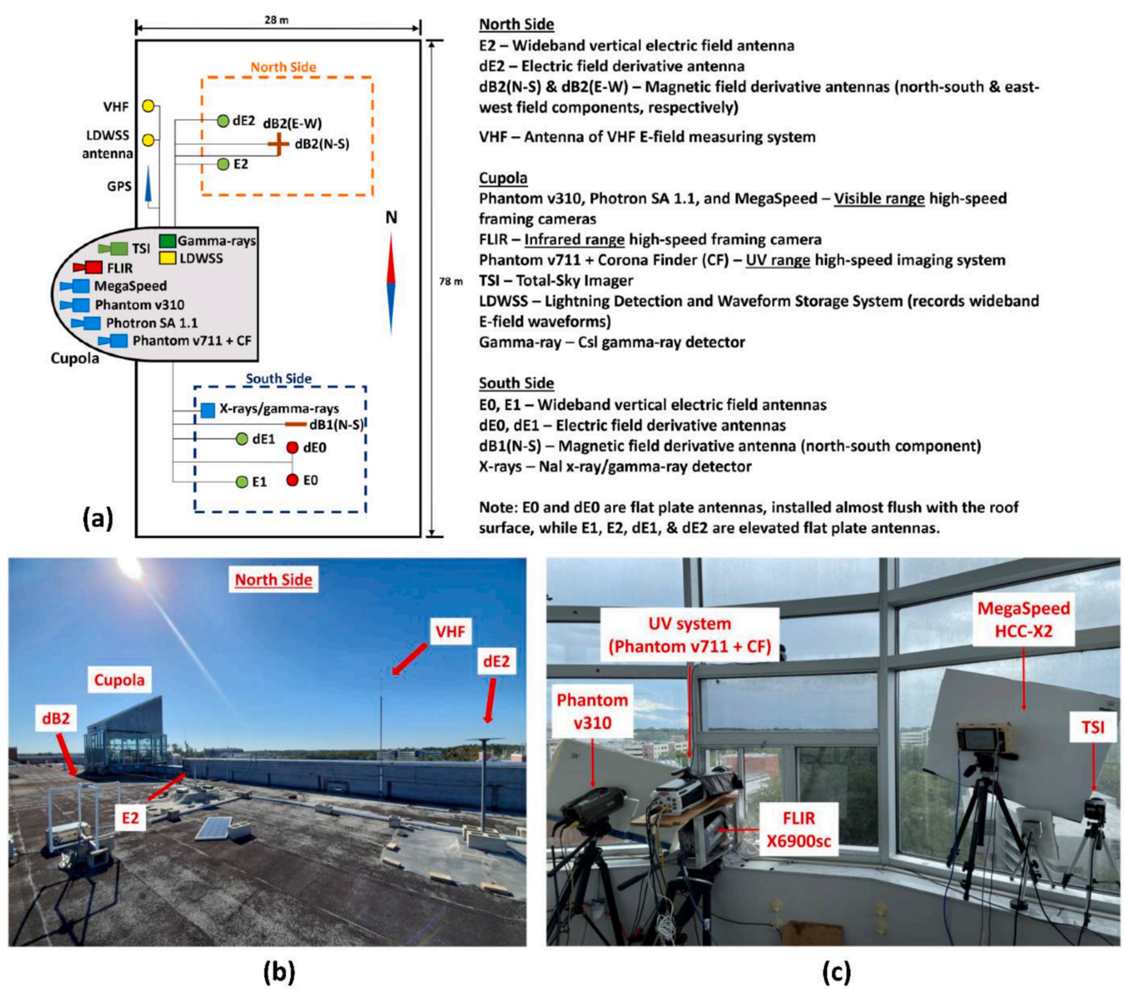

Fig. 1. Lightning Observatory in Gainesville (LOG), Florida. (a) Schematic overview, (b) photograph of the cupola (facing west) and various sensors installed on the roof, (c) photograph of the high-speed framing cameras installed inside the cupola.

visualization) of the negative leader stepping process is due to Gorin et al. (1976, Fig. 2a) [24]. It is based on experiments with long negative sparks, but is generally assumed to be applicable to stepped (and dart-stepped) leaders in negative lightning. Gorin et al.'s schematic representation of leader stepping is reproduced, for example, in Fig. 4 of Rakov and Uman (2003) [25] and in Fig. 1 of Biagi et al. (2010) [26]. Nag and Rakov (2016) [27] offered a simplified schematic reproduced in Fig. 2 of this paper. Shown in Fig. 2a is a bidirectional space leader formed below the tip of the negatively charged primary leader channel. Thinner lines represent streamers connecting the positive end of space leader with the primary leader channel and those developing downward from the negative end of the space leader. In Fig. 2b, the space leader is already connected to the primary leader channel, causing a negative corona streamer burst in the forward (downward) direction (also shown in Fig. 2c) and a traveling wave moving positive charge in the backward direction (upward, along the hot leader channel). The upward wave is analogous to a mini return stroke as discussed next.

Prior to each step (three of them are shown schematically in Fig. 2d), the leader channel is negatively charged, with the bulk of the charge being stored in the corona sheath. When stepping occurs, positive charge is injected at the tip into the hot channel core in the form of an upward-traveling wave. This positive charge serves to partially neutralize the negating corona-sheath charge (see inset in Fig. 2b that is adapted from Maslowski and Rakov (2006) [28]) and, as a result, the wave magnitude is decreasing with height. After traveling over some hundreds of meters the positive charge wave runs out of steam (becomes absorbed in the negative corona sheath), and the channel that it just traversed becomes negative again. Everything in the above description is similar to the return stroke, except for the channel being not grounded and the magnitude of positive charge injected at the tip being small compared to the negative charge stored in the channel. The negative leader process, including upward positive-charge waves, is reproduced in the numerical model of Syssoev et al. [2020; see their Figs. 7 and 8] [4]. The compensation of leader charge stored in the corona sheath is accomplished via the so-called reverse corona, which is described by Gorin (1985) [29] and Maslowski and Rakov (2006) [28].

Experimental evidence of upward-moving waves (mini return strokes) in negative leaders includes the following. Wang et al. [1999]

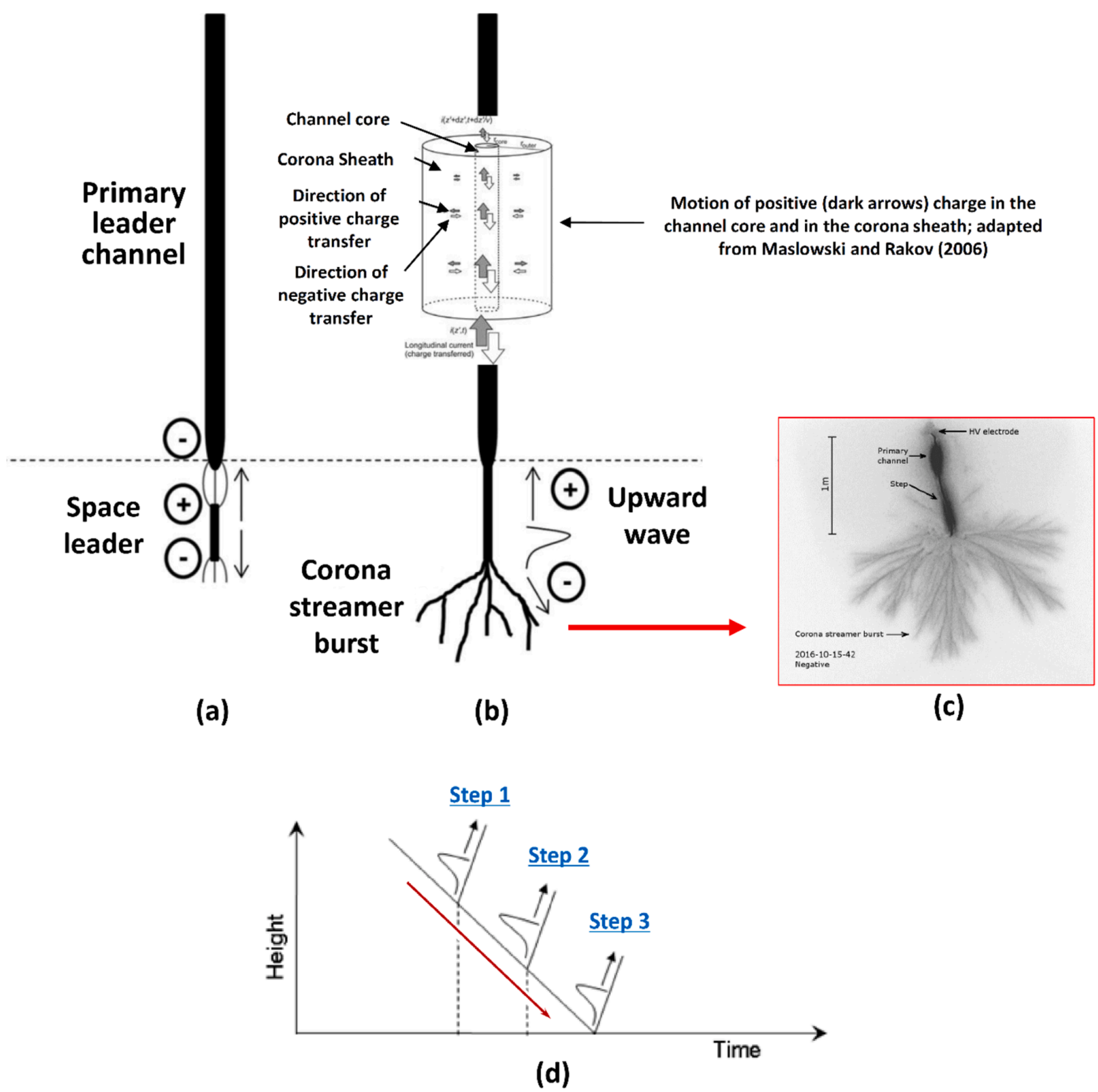

Fig. 2. (a) and (b) Schematic representation of negative leader step formation process; adapted from Nag and Rakov (2016) [27] with inset in (b) adapted from Maslowski and Rakov (2006) [28]. (c) A rare image of structured corona streamer burst in a long negative spark; adapted from Kostinskiy et al. (2018) [3]. (d) Schematic representation of three downward-leader steps; adapted from Nag and Rakov (2009) [33]. Negatively sloped arrow indicates the overall downward extension of negative leader channel. Each step current pulse originates at the tip of the downward-extending channel and propagates upward (as indicated by positively-sloped arrows), like a mini return stroke.

[30] observed, for a dart-stepped leader, upward luminosity waves propagating over tens of meters to 260 m at speeds ranging from 1.9×10^7 m/s to 1.0×10^8 m/s with a mean of 6.7×10^7 m/s. Amplitudes of luminosity pulses observed by Wang et al. [1999] [30] decayed to 10% of their original values over 50 to 100 m. For stepped leaders, the distances traversed by "mini return strokes" are expected to be larger (several hundred meters according to Krider et al. [1977] [31]), and an appreciable amount of positive charge is expected to be tranported over hundreds of meters (or more) along the channel. Winn et al. (2021) [32] reported on stepping-related current waves in upward negative leaders that traveled downward over 3 km to reach the ground. They also suggested that current (and, hence, charge) waves can travel considerably farther than their corresponding, luminosity waves. Thus, charge transfer by mini return strokes can occur over considerably larger

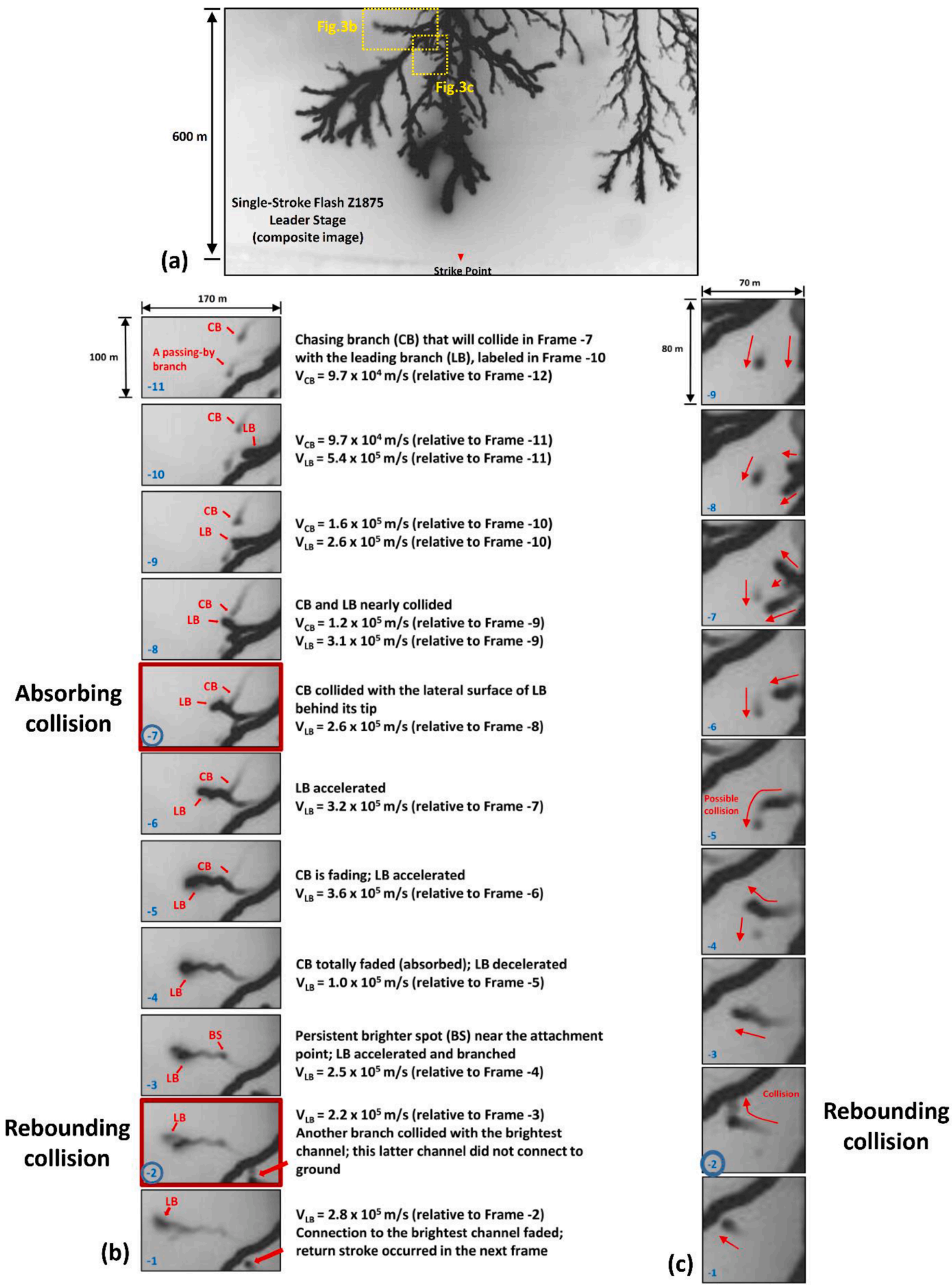

Fig. 3. Flash Z1875. (a) Composite image of the negative stepped leader of single-stroke Flash Z1875. Yellow dotted boxes mark the regions for which consecutive 50-μs Phantom frames are shown in (b) and (c).

distances (kilometers) than inferred from their luminosity waves.

In the following Section, we will present our observations of collisions of leader branches and reactivation of decayed leader branches, both phenomena being apparently facilitated by the leader stepping process.

4. Observations, analysis, and discussion

4.1. General information

We will present data for three downward negative stepped leaders that terminated on ground (or on insignificant protrusions above ground) at distances of 1.1 km (Flash Z1875), 2.5 km (Flash Z1802), and 2.4 km (Flash Z2003) from LOG. Flash Z1875 had one stroke, Flash Z1802 had three strokes (the first two strokes of which had different terminations on the ground, while the third stroke followed the first stroke channel trunk and utilized some of its branches), and Flash Z2003 had two strokes that produced different terminations on the ground. All the stepped leaders presented here were imaged when they were at altitudes of some hundreds of meters above ground and within 1 ms prior to the return-stroke onset. All the leaders were heavily branched and each of them exhibited at least some tens of active tips at its lower extremity within the field-of-view of the camera.

4.2. Collision of leader branches

Collisions of stepped leader branches were observed in flashes Z1875 and Z1802. Flash Z1875 was recorded on September 29, 2018 at 01:02:15.3976892 UTC, and Flash Z1802 was recorded on June 8, 2018 at 01:07:07.5657678 UTC. We present results for Flash Z1875 first because they are more informative, in part due to this flash being closer to LOG than Flash Z1802. Flash Z1802 was recorded by the MegaSpeed, Phantom, and FLIR cameras, while Flash Z1875 only by the Phantom camera. MegaSpeed camera records are not shown in this paper.

Fig. 3a shows a composite image of 60 inverted Phantom frames (pixel size = 2.2 m x 2.2 m) of Flash Z1875, from the frame in which the leader of Stroke 1 first entered the field of view (FOV) to the frame immediately preceding the return-stroke frame. Two overlapping yellow-dotted boxes mark the regions for which individual frames are shown in Figs. 3b and c. Similarly, Fig. 4a shows a composite image of 172 inverted Phantom frames (pixel size = 4.7 m x 4.7 m). The blue-dotted box in Fig. 4a marks the region for which individual frames are shown in Fig. 4c. Fig. 4b shows a single 1-ms FLIR frame of Stroke 1 of Flash Z1802 including the late stage of leader and the return stroke. Two collisions are seen in Flash Z1875 (Fig. 3) and one in Flash Z1802 (Fig. 4). The altitudes of collisions were between 370 m and 560 m above ground level (AGL). The process of collision usually involves two leader branches which we refer to as the leading branch (LB) and the chasing branch (CB).

Flash Z1875. In Fig. 3b, the CB enters the FOV in Frame −11 and the LB is first detectable in Frame −10. The speeds of both the CB and the LB are specified on the right-hand side of each frame. The CB propagated more or less downward, while the leading branch extended mostly horizontally. Both of them moved at normal speeds of the negative stepped leader, although the LB was always faster. The LB bifurcated in Frame −9, with the upper sub-branch apparently coming in contact with

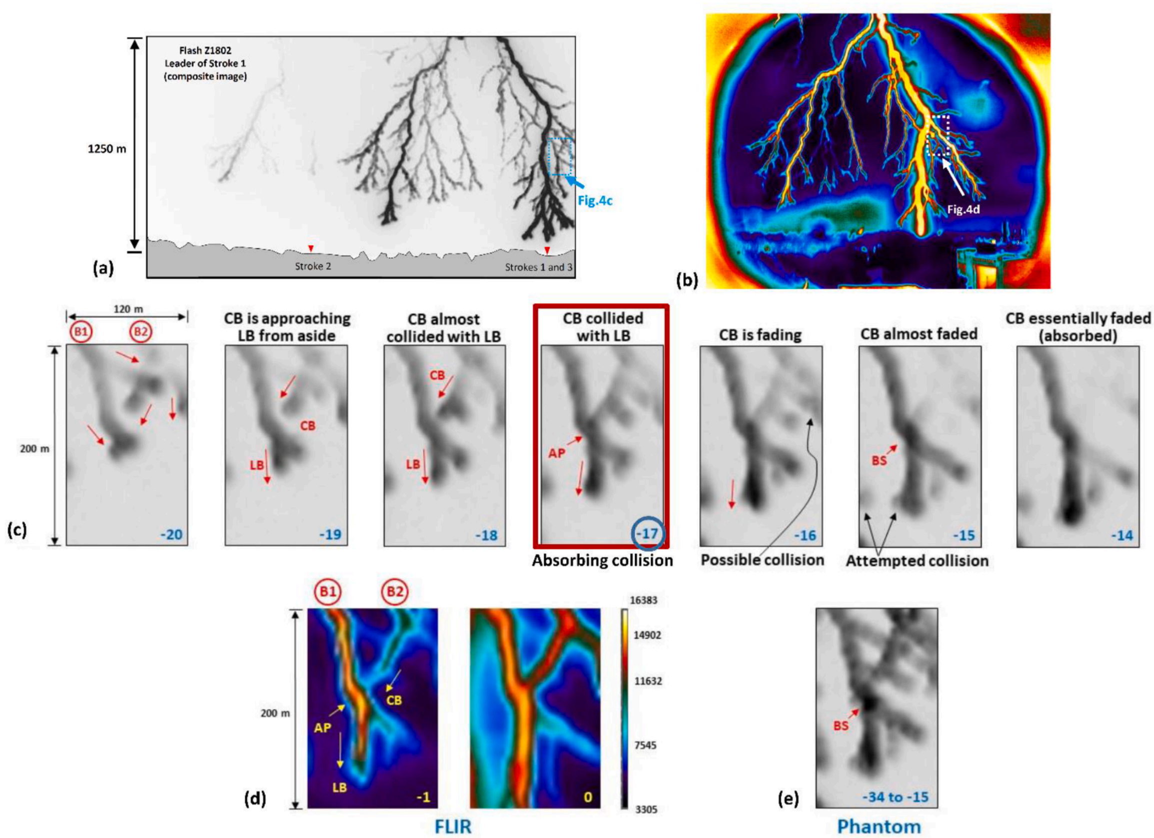

Fig. 4. Flash Z1802. (a) Composite Phantom image of the negative stepped leader of Stroke 1. Blue dotted box marks the region for which individual frames are shown in (c). (b) A single 1-ms FLIR frame of Stroke 1 including the late stage of leader and the return stroke. White dotted box marks the region for which individual frames are shown in (d). (c) Seven consecutive 50-µs Phantom frames showing the dynamics of leader branches in blue-dotted box labeled 'Fig. 4c' in Fig. 4a. (d) Two consecutive 1-ms FLIR frames, where Frame −1 is the last frame corresponding to the leader stage and Frame 0 includes both the late stage of leader and the return stroke. (e) Composite Phantom image including 20 50-µs frames approximately corresponding to the 1-ms FLIR Frame −1 shown in (d). Note a persistent brighter spot (BS) near the attachment point in (e) (also marked in Frame −15 in (c)).

the CB via a faint (streamer) link in Frame −8. The CB is clearly seen collided with the lateral surface of the LB behind its tip in Frame −7. Note that the LB accelerated between Frames −9 and −8, decelerated between Frames −8 and −7, and again accelerated between Frames −7 and −6 and between Frames −6 and −5. The LB shows enhanced brightness (luminosity blooming) near the leader tip in Frames −5 and −4 and branching in Frame −3. The CB is seen connected to the LB in Frames −7 to −5. It became undetectable (apparently absorbed by the LB) in Frame −4. Note a persistent brighter spot (BS), marked in Frame −3, near the collision point. This brighter spot remained detectable until the return stroke onset (Frame 0, not shown in Fig. 3b). The CB apparently served to feed its negative charge into the LB.

Fig. 3c shows an 80 m x 70 m region which overlaps the region shown in Fig. 3b (see Fig. 3a). One collision via a relatively faint (streamer) link is seen in Frame −2 (it is also seen in Fig. 3b). Another possible collision is seen in Frame −5. Also seen in Fig. 3c are frequent changes in branch direction (indicated by red arrows) and appearance/disappearance of relatively bright branches (compare, for example, Frames −7 and −6), which, along with collisions, are indicative of a highly-structured and rapidly-changing local electric field pattern.

Flash Z1802. In this flash, a clear collision is seen in Frame −17 (where AP stands for the attachment point) in Fig. 4c (also in Fig. 5 introduced in Section 4.3). The collision scenario in Fig. 4c is generally similar to that seen in Fig. 3b. The CB approached the LB from aside, collided with the lateral surface of the forked LB, and gradually faded away (became absorbed by the LB). Note that a streamer-like link was established between CB and LB in frame −18. Similar to Fig. 3b, a brighter spot near the AP is seen in Frames −16 to −14. Attempted collision marked in Frame −15 was identified via the reduced gap between the branches involved in Frame −15 relative to Frames −16 and −14.

4.3. Reactivation of decayed leader branches

Reactivation of decayed (non-luminous) negative stepped leader branches will be illustrated using data for two flashes, Z1802 (also discussed in Section 4.2) and Z2003. Flash Z2003 was recorded on July 2, 2020 at 19:20:42.13854851 UTC. We will present one case for Flash Z1802 and four cases for Flash Z2003. All of them were recorded by both the Phantom and FLIR cameras (FLIR camera data are not presented here).

Reactivation of decayed leader branches is brief and usually involves a bidirectionally extending luminous channel developing along the remnants of the decayed branch and making connection to the main

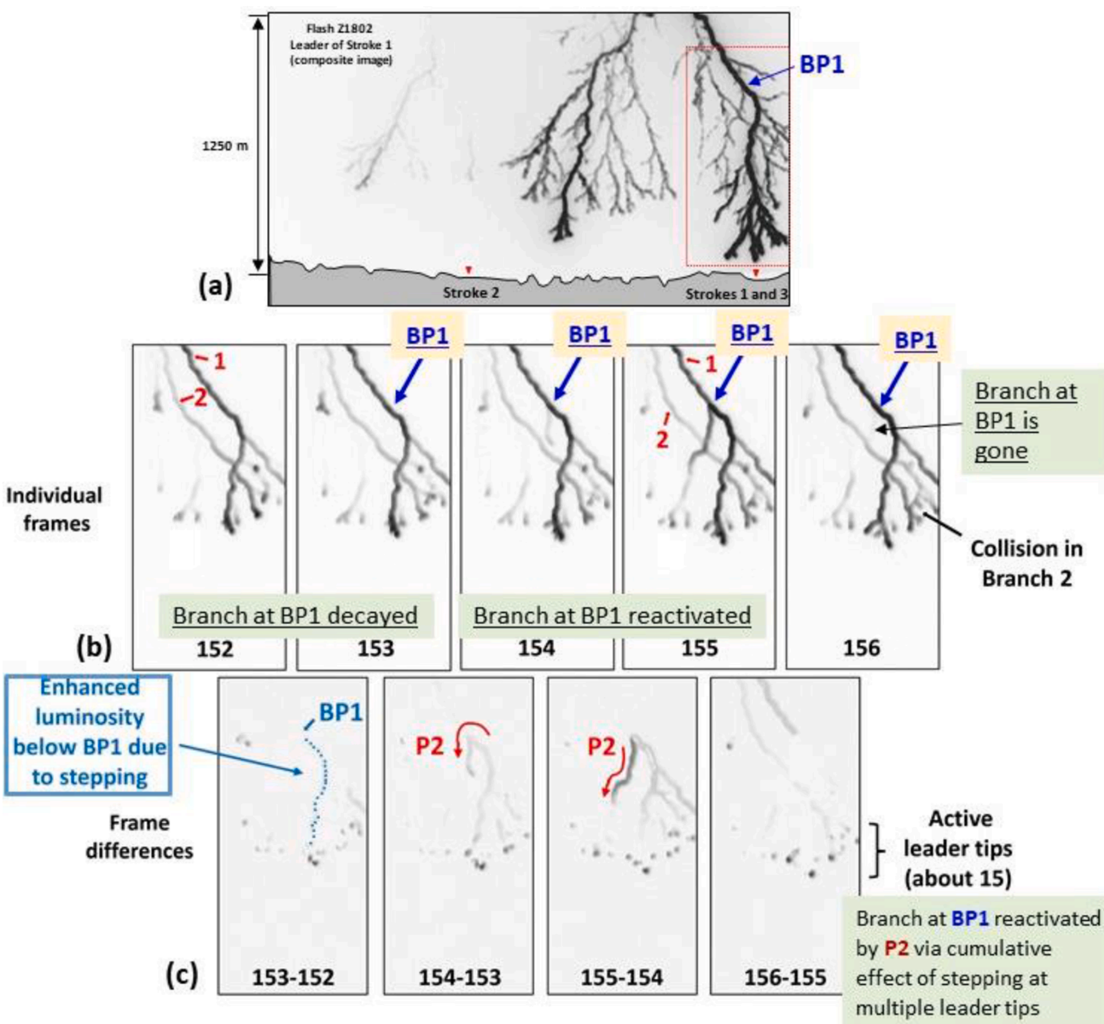

Fig. 5. Flash Z1802. (a) Composite Phantom camera image of the leader of Stroke 1. Red dotted box marks the region for which individual frames and frame differences are shown in (b) and (c), respectively. Interframe interval is 50 μs. BP1 stands for Branching Point 1. Two major branches are labeled 1 and 2 in Frames 152 and 155. Luminosity transient is labeled P2 in differential frames (frame differences) 154–153 and 155–154. Transient P2 was preceded by enhanced luminosity (faint, but clearly visible in the original image and visualized by blue dots in this figure) of Branch 1 below the branching point labeled BP1 in differential frame 153–152. Adapted from Ding et al. (2020) [11].

channel. We will refer to those luminous channels as luminosity transients or just transients. We interpret their occurrence as being caused by the stepping-related waves moving positive charge from the tip upward along the main channel to the branching point, although other interpretations are possible (e.g., Stolzenburg et al., 2015 [12]), as discussed in Section 1.

Ding et al. (2020) [11] examined different contexts in which the transients re-illuminating decayed branches aloft occur and found that 42% (lower bound due to the 50-μs interframe interval) of them were preceded by not very bright but detectable main-channel luminosity enhancement (MCLE) between the leader tip and the branching point. Such events, which constitute evidence of the stepping-related mechanism of branch reactivation, are presented in Figs. 5 and 6 (one adapted from Ding et al. (2020) [11] and four new ones).

Composite images of stepped leaders of Flash Z1802 and Flash Z2003 are shown in Figs. 5a and 6a, respectively. Red dotted-boxes in Figs. 5a and 6a mark the regions for which individual frames are shown in Figs. 5b – c and 6b – c, respectively. Transients (if any), moving leader tips, and main-channel luminosity changes are accentuated in the frame differences (differential frames), which are obtained by subtraction from a given frame the preceding one.

Luminosity transient labeled P2 is seen in differential frames 154–153 and 155–154 (see also individual frames 154 and 155) in Figs. 5b – c. It was preceded by MCLE extending over about 500 m from the lower leader extremity to the branching point BP1, seen in differential frame 153–152. Figs. 6b – c show, in the same format, four transients (P8a, P9, P10, and P8b) that occurred in Flash Z2003. Similar to transient P2 shown in Fig. 5, transient P8a (see differential frame (−14)-(−15) in Fig. 6c), was preceded by luminosity enhancement in the main channel between the lower leader extremity and the branching point labeled BP1, although not all the way to BP1. The difference between P2 in Fig. 5 and P8a in Fig. 6 is that P8a occurred at a larger distance (about 800 m) from the active leader tips and that the upward step-current wave apparently gave rise to one more transient (at BP3) labeled P9 in differential frame (−13)-(−14). Transients P8b and P8a were associated with the same branching point BP1. Transient P9 was associated with branching point BP3 and P10 with branching point BP2. Fig. 6 illustrates the complexity of branch reactivation process. It may involve multiple steps and a transient in one branch can trigger (or assist with triggering of) a transient in another branch.

4.4. Further thoughts and inferences

Any downward lightning leader (whether it exhibits detectable stepping or not) serves (1) to create a conducting path between the cloud charge source and the ground and (2) in effect to distribute charges “taken” from the cloud source along that path. Negative leaders developing in virgin air are distinctly stepped. It is generally thought that the stepped leader involves both a stepping (transient) process, described in detail in Section 3, and a more or less continuous charge transfer along the channel, with the associated steady current being of the order of 100 A (e.g., Rakov and Uman, 2003, Ch. 4 [25]). The longitudinal steady current is high enough to keep the leader channel core in a hot, high-conductivity state. An engineering model including both the background steady leader current and the superimposed stepping transients was developed by Nag and Rakov (2016) [27].

It is likely that the descending lightning leader (whether it exhibits detectable stepping or not) is energized at its lower end, as seen in Fig. 9a of Ding et al. (2020) [11], who demonstrated this for negative stepped leaders imaged with a high-speed camera operating in the medium-to-far (3 – 5 μm) infrared range. If so, then each active leader tip can be viewed as a source where negative and positive charges are separated via electric breakdown of air near the tip.

In the case of negative dart leader, which appears to move continuously along the decayed but still warm channel, negative charge is pushed forward in the form of corona streamer zone mostly guided by the existing warm channel, while positive charge is injected into the hot core behind the tip and travels in the backward direction toward the cloud charge source. Higher-frequency components will travel at speeds of the order of 10^8 m/s, comparable to that of the return stroke, but will attenuate rapidly (within a few hundreds of meters or so), while lower-frequency components will propagate at lower speeds but over longer distances, probably all the way to the cloud charge source (Rakov, 1998 [34]).

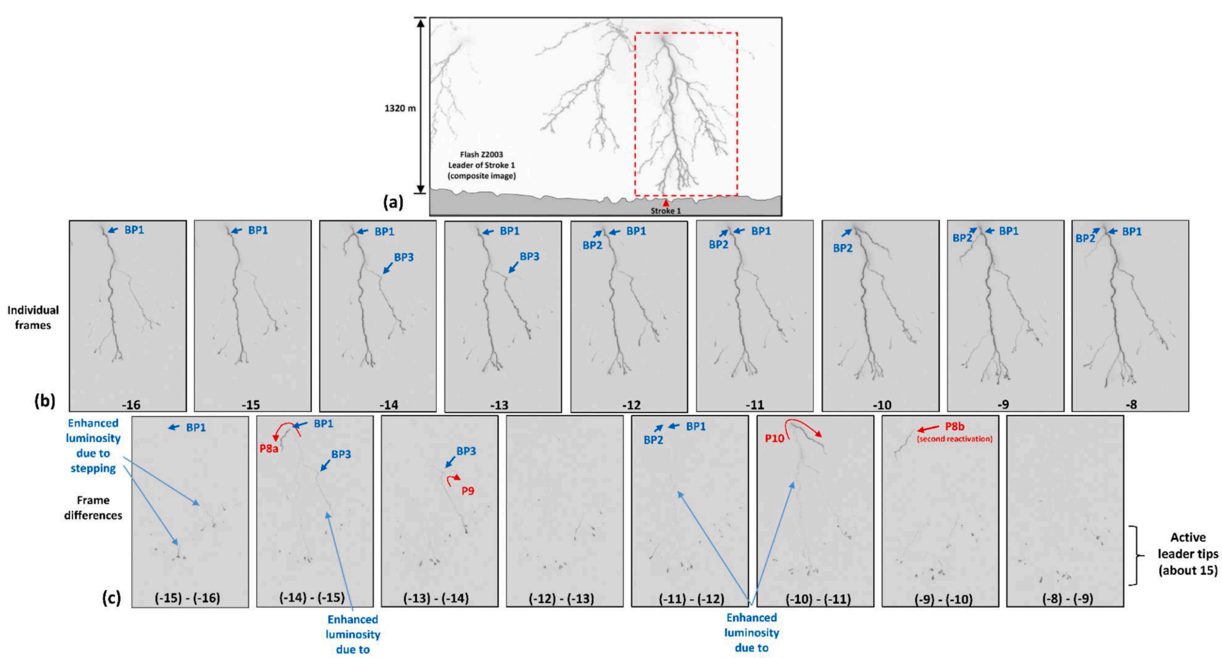

Fig. 6. Flash Z2003. (a) Composite Phantom camera image of the leader of Stroke 1. Red dashed-line box marks the region for which individual and differential frames are shown in (b) and (c), respectively. The enhanced luminosity due to stepping is faint, but clearly visible in the original images. Interframe interval is 50 μs. See text for details.

In the case of negative stepped leader, the process is more complex in that there will be also transients associated with the connection of space leaders to the primary leader channel, as shown schematically in Fig. 2. These stepping-related transients are superimposed on the longitudinal steady current in the channel core, which may be the cumulative effect of many steps (e.g., Bazelyan and Raizer 2000 [35]). Probably all leaders exhibit some level of stepping which may be unresolved with either optical or RF instrumentation. This speculation is supported by the production of X-rays (usually attributed to stepping) by dart leaders (e.g., Dwyer et al., 2004 [36]) and observation of leader stepping in positive lightning and sparks (e.g., Kostinskiy et al., 2018 [3]), which both can exhibit either continuous or intermittent mode of propagation and even switch from one mode to the other. Clearly, stepping cannot be optically resolved if the step length is comparable to the size of the leader tip. And after all, it is difficult to imagine that the current continuity equation can be satisfied for an extending leader carrying a DC current, which is what the absence of stepping apparently implies.

During the stepping process, the transients moving positive charge along the hot core are likely to interact with the negative space charge stored in the surrounding corona sheath, as well as with decayed and active leader branches that happen to be nearby. It appears that the effects described in Sections 4.2 and 4.3 are in support of this expectation. We further speculate that some other phenomena that are indicative of radial discharge processes near the developing leader channels (such as needles; e.g., Hare et al., 2019 [37]; Pu et al., 2019 [38]) may be also related to the injection of stepping-related charge into the hot core behind the tip (polarity of the injected charge is opposite to that of the corona sheath), causing the transient reversal of the radial electric field inside the corona sheath, near the core. In our opinion, this may happen in leaders of either polarity, although for negative leaders the expected radial positive breakdown (not observed to date) is more difficult to detect with either VHF or optical instruments.

It is worth mentioning that, during the return stroke, the transverse (radial) discharge processes are well known (e.g., the so-called reverse corona; Gorin, 1975 [29]; Maslowski and Rakov, 2006 [28], 2009 [39]) and have been observed for either polarity (see Lebedev et al. (2007, Fig. 8) [40] for negative lightning and Wu et al. (2021 [41], 2022 [42]) for positive lightning). The data (single frame) for negative lightning reported by Lebedev et al. are unique in that they were obtained with an image-converter camera K004 operating with an exposure time of 13.4 μs and an optical gain of 10^4 at a distance of about 500 m from the natural-lightning channel. Weak branches whose lengths ranged from 1 to 3 m extending in seemingly random directions from the lateral surface of the return-stroke channel were observed. Those branches were very faint and their visualization required image enhancement followed by a reconstruction procedure. Lebedev et al. (2007) [40] interpreted the faint branches as the return-stroke reverse corona (positive streamers) neutralizing negative charge stored by the preceding leader in the corona sheath.

The wave moving positive charge up and compensating negative charge in the corona sheath aloft can be alternatively viewed as an upward-moving potential discontinuity serving to drain negative charge from the corona sheath at progressively higher altitudes and transport it down to the tip. In this latter view, the corona sheath acts as a depository of negative charge, which helps (when tapped by the stepping-related waves) to supply an additional amount of negative charge to the leader tip. Equivalence of the two above interpretations, compensation of negative charge in the corona sheath and draining of negative charge from the corona sheath, as applied to return-stroke models, has been demonstrated by Maslowski and Rakov (2007) [43].

5. Summary

1 A negative stepped leader branch tip can collide with the lateral surface of an adjacent (leading) branch, usually at an angle of about 90°. Collision can be caused by the attracting Coulomb force of the upward moving positive charge wave caused by stepping at the leading branch tip.
2 A heavily-branched negative leader creates a highly-structured and rapidly changing electric field pattern inside and in the vicinity of the volume it occupies.
3 Branches formed at earlier negative leader stages (at higher altitudes) may lose their connection to the main channel and decay (become non-luminous). Stepping-related waves moving positive charge from the leader tip up along the hot leader channel can reactivate decayed negative branches at higher altitudes, possibly via cumulative effect of stepping at multiple active leader tips.
4 Stepping-related waves moving positive charge upward along the hot negative leader channel core resemble mini return strokes. This positive charge can interact with the negatively-charged leader corona sheath, as well as with decayed or active negative branches that happen to be nearby.

Data availability

All the data and results for event Z1875, Z1802, and Z2003 can be found at: https://doi.org/10.6084/m9.figshare.19074365

CRediT authorship contribution statement

Z. Ding: Conceptualization, Methodology, Software, Data curation, Writing – original draft. **V. A. Rakov:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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