Branched Dart Leaders Preceding Lightning Return Strokes

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ABSTRACT: This study describes the occurrence of branches in lightning dart leaders, based on data acquired in Florida using a high-speed video camera and electric field change sensors. More than half (57%) of 72 flashes with analyzable dart leaders show at least one successful branched dart leader (BDL), and 9 flashes have two successful BDLs. Overall, 18% of 282 visible successful dart leaders are branched. Most (42 of 50) cases of BDLs occur in the first dart leader after a stepped leader/return stroke sequence, and the data indicate 55% of first dart leaders are visibly branched. Compared to first dart leaders in the 31 flashes without any branched dart leaders, BDLs tend to follow stepped leader/return strokes with significantly larger average peak currents (-31.3 vs. -20.6 kA) and shorter average interstroke intervals (71.94 vs. 94.64 ms). Average peak current of BDL strokes is 62% larger (-17.8 vs -11.0 kA) than for unbranched first dart leader strokes. Branched dart leaders generally travel in the some of the most recently used lightning channels, but they are not always within the main channel of the prior return stroke. Successful BDLs may dart all the way to ground when in a prior stroke channel, or they may become stepped leaders when they reach the lower end of the prior stroke branch. Electric field change data for all the BDL cases exhibit an erratic pulse character for at least part of the leader duration; in some cases, the erratic character ends when the branches vanish. This paper is based on *Stolzenburg et al.* [2014].

INTRODUCTION

In much of the lightning literature, it is stated that the dart leaders preceding subsequent return strokes in cloud-to-ground (CG) flashes typically do not branch. *Schonland and Collens* [1934] studied the progression of normal, negative CG flashes using a Boys camera. Based on 41 photographs of 95 CG flashes and more than 200 return strokes, *Schonland et al.* [1935] found that the first leader to ground was stepped and highly branched, the first return stroke (RS) was also branched, and most leaders before subsequent RSs were not stepped but instead were dart leaders that "follow the path blazed by the first leader but usually do not branch." Two examples of branched dart leaders are in *Schonland et al.* [1938].

Advances in high-speed video cameras have allowed a better view of dart leaders and the RSs that precede and follow them in triggered and natural lightning flashes. *Winn et al.* [2012] report on a triggered flash in which three 100 m "spurs" are visible as a dart leader passes the junctions of former branches, and these "spurs" illuminate during the subsequent RS. *Stolzenburg et al.* [2013a] show three examples of branched dart leaders in which the subsequent RSs are also branched, illuminating some of the dart leader branches. *Stolzenburg et al.* [2013b] provide one other case of a branched dart leader. These examples, along with the evolved notion of the rarity of branched dart leaders, motivated us to examine our entire

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video dataset of 154 flashes for additional cases. We herein describe several varieties of successful branched dart leaders observed in time-correlated high-speed video and E- change data. In our usage, a *successful* dart leader is one in which at least some part of the leader reaches ground and results in a return stroke. Our results indicate that successful branched dart leaders are quite common, occurring in more than half the 72 flashes with analyzable dart leaders.

DATA SOURCES

Time-correlated data for natural CG flashes were collected around Kennedy Space Center in Florida during July-August 2011. Flat-plate E-change antennas [e.g, *Kitagawa and Brook,* 1960] were operated from ten locations. Data used herein were collected with instrument decay time constant of 1 s, bandwidth of 0.16 Hz-2.6 MHz, and sample rate of 5 MS/s. The "physics" polarity convention is used. Location and peak current of RSs are obtained from the Cloud-to-Ground Lightning Surveillance System, a network of medium-gain VLF/LF sensors, with missing values derived from the E-change data. Optical data were acquired with a Vision Research Phantom® V12.1 high-speed video camera equipped with an 8 mm focal length lens. Capture rate was 50,000 frames per s (20 μs image interval) with 19.6 μs exposure time per frame. Resolution of images is derived using the distance to the RS. Return strokes are referred to by their order within the flash, e.g., RS2 for the second RS. When discussing subsequent leaders in the video data, we use the generic term 'dart leader,' since we cannot distinguish between continuous dart, dart-stepped, and 'chaotic' leaders. The E-change data allow us to discriminate between these subsequent leader types.

RESULTS

Our results on occurrence statistics and comparison of flashes with and without BDLs are summarized in the Abstract and fully described in *Stolzenburg et al.* [2014]. Herein we briefly describe their physical characteristics, with the more complete summary given in the above-cited paper. Within our dataset of 41 flashes, two basic modes of BDLs are distinguishable: (A) those travelling in the prior RS channel and its branches, and (B) those travelling only in major branches of the prior stepped leader and RS. Combinations of these modes are also seen, hence we categorize our 50 BDLs into four groups:

- Type 'A' in which the dart leader follows the path of the prior RS and branches into many of the same major and minor branches along its progression to ground (25 cases).
- Type 'A2' in which the main dart leader travels in the prior RS channel while the only branches visible are at upper levels, and these are within major branches of the prior stepped leader (7 cases).
- Type 'B then A' in which multiple dart leader branches extend, branch, and subsequently dim (and may begin stepping) when they reach the ends of the former stepped leader branches that they are following, then one dart leader branch emerges and proceeds to ground in the former RS channel (13 cases). In some cases (6 of 13) the branch of the BDL that reaches ground has visible sub-branches.
- Type 'B then stepped' in which the branched dart leader travels along former branches only, and when it reaches the extent of the former branches it becomes a stepped leader to ground from one or several of the former branch ends (5 cases).

Images from a flash with 'Type A' BDL that was 12.6 km from the camera are shown in **Figure 1**. The top of the frame is 6.9 km altitude, and the leaders and strokes are visible up to 4.87 km. The stepped

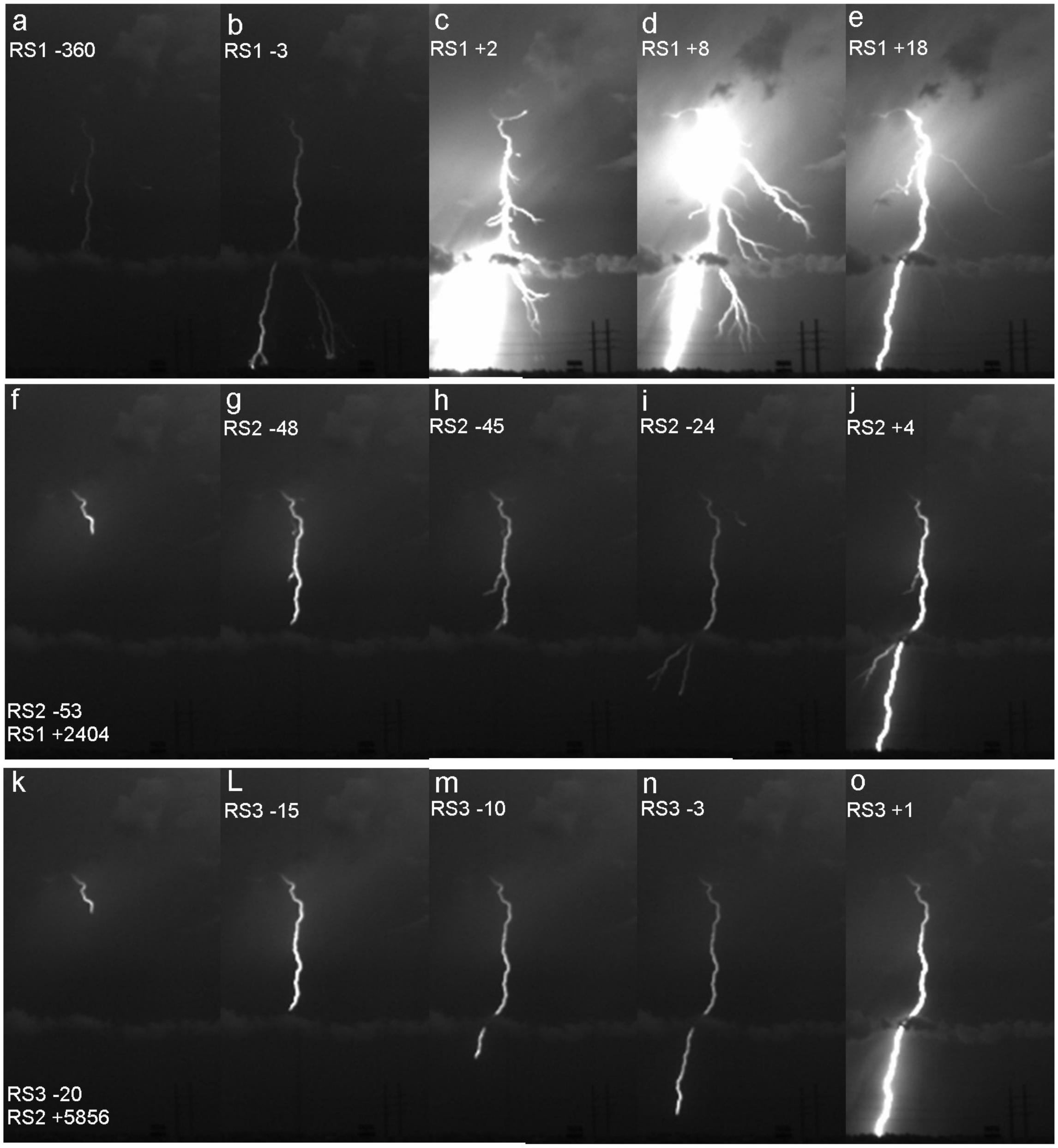

Figure 1. Cropped, unenhanced video frames of the stepped leader before RS1 (top row) and branched dart leader before RS2 (middle row) for a flash at 1909:50 UT, on 26 July 2011. Camera frame number relative to the return stroke is given for each frame. Video frame rate was 50,000 ips; exposure per image was 19.6 μs. Frame top altitude is 6.9 km, and image pixel resolution is 31.50 m. Dart leader to RS3 (bottom row) shows no branches and travels about 2.5 times faster than the branched dart leader to RS2.

leader preceding the first RS (Figs. 1a-b) shows multiple branches at upper levels and two main branches (with sub-branches) below 2.3 km. Many of these branches are visible again beginning 40 μs after RS1 (Fig. 1c), when the image saturation decreases adequately along the channel. By 160 μs after RS1, much longer portions of the upper branches illuminate (Fig. 1d), and some of these branches remain lit for another 200 μs (Fig. 1e) or more. When the dart leader emerges 48.02 ms later, it is relatively bright and within the former RS channel; the fourth frame with this leader is in Figure 1f. Branches first appear along the dart leader 120 µs later, and these extend in some of the branches that were obvious after the preceding RS. This dart leader continues to show branches for 760 µs of its entire 1.12 ms (e.g., Figs. 1g-i). When the BDL tips reach 1 km altitude, their downward progress slows, their luminosity decreases, and then they disappear. This sequence is different from that seen in the BDLs of other flashes, which are clearly branched until the subsequent RS occurs. Here, the subsequent RS2 illuminates all the BDL branches; one image from 80 µs after RS2 is in Figure 1j. For comparison, Figures 1k-n show the progression of the next dart leader of this flash. It was not branched and follows the prior channel to ground in 0.46 ms (23 frames, compared to 56 frames for the BDL before RS2). As shown in Figure 1o, the following RS3 was unbranched. The next 10 dart leaders and RSs of this flash were similarly unbranched.

Figure 2 shows the E-change data for the BDL stroke of this flash. The leader began with relatively small-amplitude pulses about 0.5 ms before the dart leader appeared in the video. Pulses occurred at variable but short intervals, and their amplitudes varied from two to three times the background noise level. The pulse amplitude increased, and the character became more erratic (i.e., widely varying amplitude from one pulse to the next, along with short and variable pulse interval) about 0.1 ms before the leader became visible. The pulse amplitude then decreased at about the same time when the branches first appear, although the erratic nature continued. As noted, the branches stop progressing and begin to dim soon after the time shown in Figure 1i; this change is nearly coincident with end of the erratic leader E-change structure indicated in Figure 2. During the final 0.3 ms (lowest 880 m), the leader E-change is characteristic of a dart-stepped leader, with semi-regular pulse interval of about 5 µs. Seven additional examples of Type A and Type A2 BDLs are shown and described in *Stolzenburg et al.* [2014].

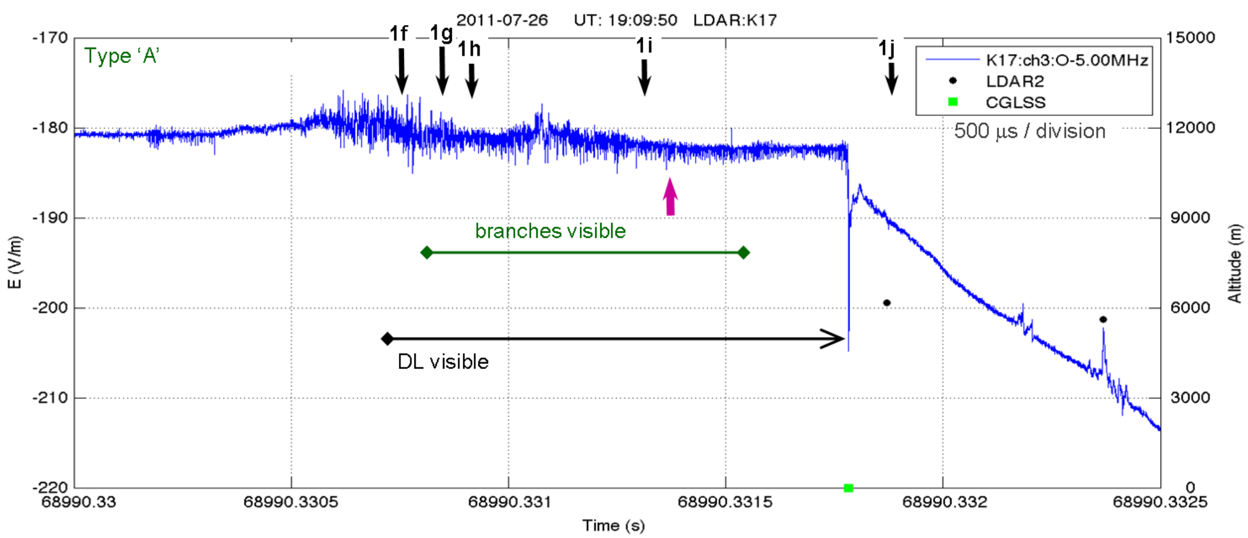

Figure 2. E-change for 2.5 ms for Type 'A' BDL. Time scale is in seconds after 00 UT, with 500 µs between axis divisions. Time when multiple branches are seen in the video is indicated by green line; full period when dart leader (DL) is seen is indicated by horizontal black line at the leader's top visible altitude (right axis). Purple arrow shows when E-change structure becomes less 'erratic' (and more like dart-stepped) in pulse amplitude and interval. End times of video frames shown in Figures 1f-1j are marked.

An especially brilliant case of a Type 'B then A' branched dart leader is shown in **Figure 3**. In this case the preceding stepped leader and RS1 have multiple long branches (Figs. 3a-3d) extending below cloud. The subsequent BDL is first visible only in branches and not in the former channel (Fig. 3e); these

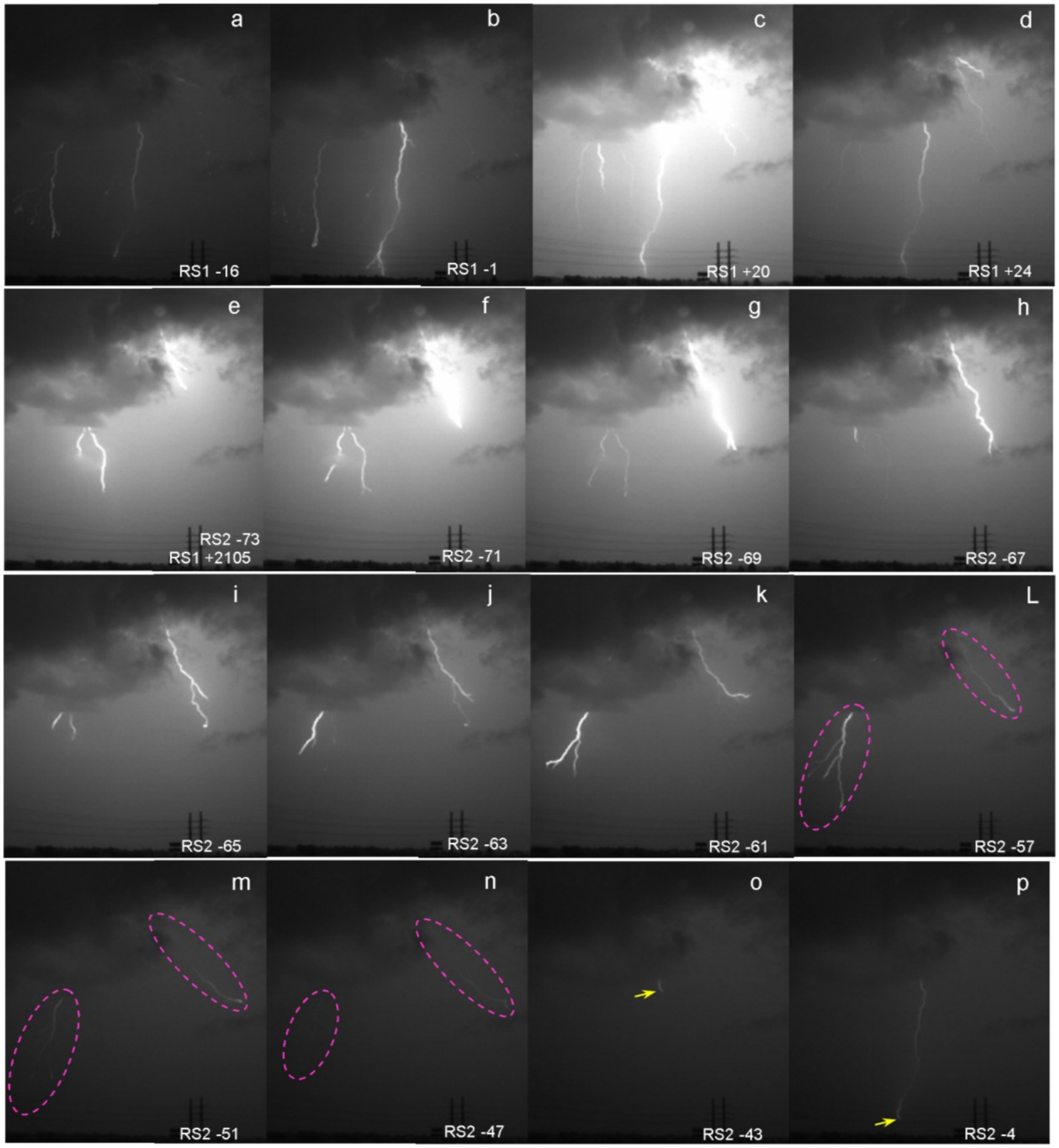

Figure 3. As in Figure 1, except showing cropped, unenhanced video frames for first two strokes of a flash at 2312:17 UT on 14 August 2011. Frame top altitude is 3.4 km, and image pixel resolution is 16.00 m. Stepped leader and first RS are shown in top row (a-d). Earliest dart leader branches saturate portions of the images in (e) - (g) while traveling only in branches of RS1. Ellipses in (L) - (n) show region of two BDL branches as they fade. Dart leader branch to ground is much dimmer but visible in (o) and (p); lower end is indicated by arrow.

branches extend bright and fast (Figs. 3f-i), then dim as they reach their respective ends (Figs. 3j-n). After about 640 μs of visible advance the branches fade, then the main leader emerges from cloud (Fig. 3o). This leader propagates relatively slowly and dimly to ground (Fig. 3p), with a few short branches visible briefly near cloud base. In the E-change data (**Figure 4**), the pulse character is highly erratic from the beginning of the leader. The erratic nature and pulse amplitude distinctly diminish as the branches fade; at this time, the main leader is 1600 m above ground. Soon after the time when main leader emerges, the pulse interval becomes semi-regular but relatively short (about 3 µs). The final 200 µs of E-change data, with slightly larger amplitude pulses, are typical of a dart-stepped leader. The subsequent RS2 saturates the area of the right upper branch, so we cannot tell if that branch lights after the RS. However, the left branch does illuminate, along with most of its sub-branches, over a period of 500 µs. RS3 of this flash was also preceded by a BDL, in which only the left branch and main channel were visible concurrently (Type ‘A’), and the dart leader advanced relatively quickly and brightly to ground. RS4 in this flash was preceded by an unbranched dart leader in the former left branch only. This dart leader branch became a stepped leader 320 m below cloud, which went to a new ground location. Details of this are in *Stolzenburg et al.* [2014], along with four other good examples of Type ‘B then A’ and Type ‘B then stepped’ BDLs.

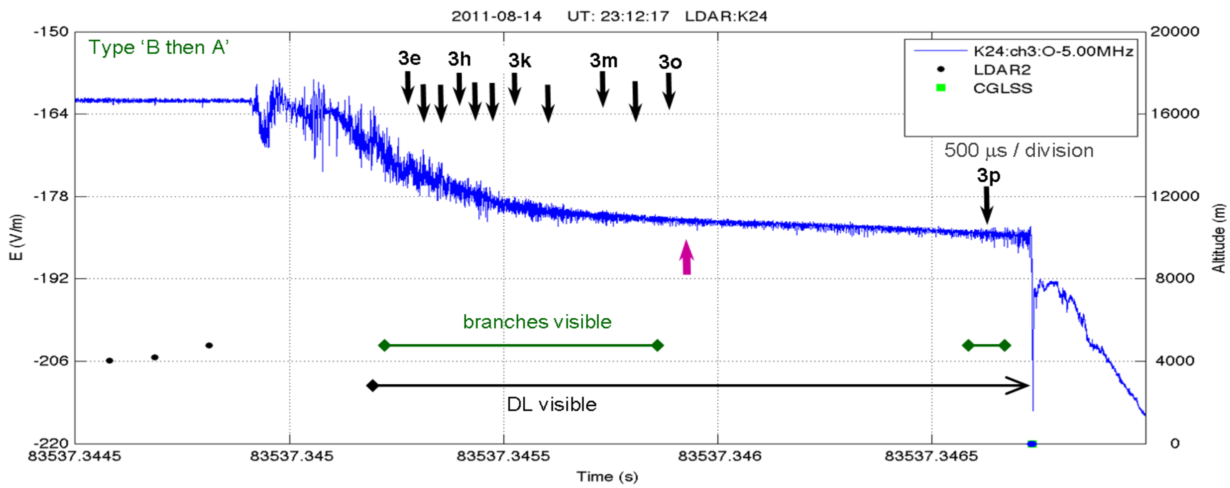

Figure 4. As in Figure 2, for a Type ‘B then A’ BDL. End times of frames in Figure 3 are marked. E-change data for 2.5 ms are shown, with branches visible from near the beginning of the DL appearance. Transition in pulse character from ‘erratic’ to more like that of a dart-stepped leader occurs soon after the branches vanish.

CONCLUSIONS

For this study [based on *Stolzenburg et al.*, 2014], we categorized 50 BDL examples from their appearance in the video data. Our most common (A) mode of BDL may not be surprising, since these main channels and late branches may be carrying the largest currents latest in the prior RS and thus are all obvious choices for the propagating dart leader to travel in. We note, however, that not all prior branches are involved in even these most common types of BDLs. The cases of the (B) mode of BDL show that all dart leaders do not propagate in a prior RS channel. These cases reveal what happens when a dart leader follows only the prior branches: because these former branches did not reach ground, the dart leaders traveling within them stop their progress as dart leaders when they reach the ends. Many attempted dart leaders fail in this manner. In order to make a return stroke, the successful BDL must either start propagating in the branch that formed the prior connection to ground, or it must become a stepped leader at its ends. For the latter situation, we note that this is a distinctly different sequence than the one often used to describe dart leaders that become stepped leaders as having *diverted* from the prior channel.

The E-change data for the BDL cases exhibit an erratic pulse character for at least part of the leader duration. This erratic nature usually begins at the start of the leader E-change and continues as the branches become visible. The erratic character ends before, during, or after the time when the branches vanish from view. In most cases, the E-change data become less erratic when the leader is near ground, more closely resembling the pulse character of dart-stepped leaders through the last 100-200 μs. In a few cases, the erratic pulse character clearly ends and changes to regular dart-stepped pulses at nearly the same time as the branches fade from view. These coincident examples tempt us to think the erratic character and branches may be causatively related, although there are cases elsewhere in our dataset for first and relatively bright dart leaders in which the E-change data show erratic character without visible branches.

ACKNOWLEDGMENTS

This project was supported by the National Science Foundation (grant AGS-1110030) and the NASA/Mississippi Space Grant Consortium (grant NNX07AM36A). The video camera was made available via NSF grant AGS-0813672. We greatly appreciate the time, expertise, and generous loan of camera equipment that Tom Warner has provided to this project. We also thank Lauren Vickers, Chris Maggio, and Clay Conn for their tireless work during the data collection. Text and figures in this document are from *Stolzenburg et al.* [2014], published and copyrighted by AGU/Wiley Publishers.

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