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Bi-directional Discharges Occurring at the Tip of Dart Stepped Leaders in Rocket Triggered Lightning

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***Abstract*—Using a high-speed optical imaging system specifically designed for observing the lightning attachment process, we have observed the discharges occurring at the tip of dart stepped leaders of rocket triggered lightning with a time resolution of 0.1 µs and a spatial resolution of about 1.4 m. It was found that the progression of a dart stepped leader is effectively a series of bi-directional pulse discharges. The progression features in the two opposite directions of each pulse discharge are different. The upward progression tends to have a more or less constant speed of a few 10^7 m/s. In contrast, the downward progression usually exhibits a similar initial speed as the upward progression, but sometimes the speed drops to a value about one order of magnitude smaller than the upward speed after propagating a distance of about 2 m. In addition, the downward discharges are found to be generally weaker and to propagate in much shorter distance than the upward discharges. All the bi-directional discharges initiated at a location immediately below where the downward part of its previous bi-directional discharge reached.**

Keywords—lightning; stepped leader; dart stepped leader; step formation

I. Introduction

More and more evidence has been published indicating a bright step of lightning stepped and dart-stepped leaders is formed by the connection of a forward progressing leader and a backward space leader [e.g., Biagi et al., 2010; Hill et al., 2011; Gamerota, 2014; 2015] as first sketched by Gorin el al. [1976] for laboratory long gap discharge stepped leaders. Figure 1 is the reproduction of Figure 1 published by Gamerota et al. [2014] for a dart-stepped leader contained in a rocket-triggered lightning discharge. The bright step in frame 6 is apparently formed by the connection of the space leader in frames 3, 4 and 5. However due to the limited temporal resolution of 1.54 µs (1.16 µs exposure time and 0.38 µs dead time between frames) of Figure 1, how the bright discharge in Frame 6 progresses is actually unknown. We have attempted to resolve the bright step with a time resolution of 0.1 µs and a spatial resolution of about 1.4 m using an optical imaging system called LAPOS (Lightning Attachment Process Observation System) [Wang et al. 2011, 2013]. This paper is a report of our observed results.

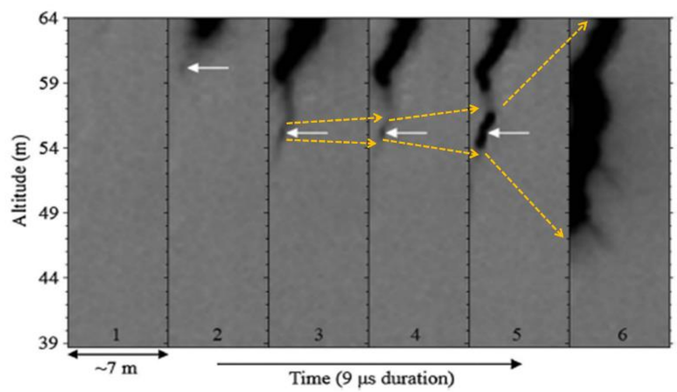

Fig. 1. Six consecutive high speed video frames of 6th leader of UF 13-10. Adapted from Gamerota et al. [2014]

II. Observation and Data

Since the summer of 2011, three LAPOSs, named LAPOS1, LAPOS2, and LAPOS3 have been operated at the International Center for Lightning Research and Testing (ICLRT) to observe the lightning attachment process of both triggered and natural lightning discharges. For this study, only data from LAPOS2 and LAPOS3 are used. As reported previously by Wang et al. [2011, 2013], LAPOS employs a type of photodiode-fiber optics array system with LAPOS2 having a sampling rate of 10 MS/s and LAPOS3 having a sampling rate of either 10 MS/s or 100 MS/s for different lightning channel sections. In order to resolve spatially a leader step, LAPOS 2 was intentionally focused on a vertical range of about 10 m above the rocket launcher used for artificially triggering lightning. Four dart stepped leaders recorded in 2014, as listed in Table 1, are suitable for analysis.

TABLE I. DATA LIST

Dart stepped leader No.	Time (UT)	Stroke peak current (kA)
UF 14-11 4^{th} leader	20:49:57, 21/06/2014	11.9
UF 14-11 6^{th} leader	20:49:57, 21/06/2014	11.6
UF 14-35 2^{nd} leader	18:59:55,25/07/2014	9.8
UF 14-52 4^{th} leader	21:17:13,11/01/2014	18.6

III. RESULTS

Figure 2 shows the light signals primarily from 5 channel sections of the 6th dart-stepped leader of UF 14-11 that occurred at 20:49:57, 21/06/2014 and were recorded by LAPOS 3. Time 0 in Fig. 2 corresponds to the approximate initiation time of the following return stroke. Leader light pulses can be clearly identified first at S13, then S11, S9, S7, and S5. Over the vertical range of about 40 m from S13 to S5 with a time interval of 9 µs, a total of 9 light pulses occurred. The average leader speed is estimated to be 4.4×10^6 m/s. Figure 3 shows LAPOS 2 recording of the last two leader pulses 8 and 9 in Fig. 2. The spatial resolution of Fig. 3 is about 1.4 m. At the time of -3.4 µs, the pulse 8 in Fig. 3 first appeared in L2S8, then at L2S7, L2S6, L2S5 and L2S4. The light pulse was clearly propagating downward. During the propagation over a distance of 5.5 m with a time duration of about 0.5 µs, the light pulse amplitude decreased to about 1/8 of its original value. The average speed of the first pulse is about 1.1×10^7 m/s. The pulse 9 apparently initiated at L2S3 and then propagated in bi-directional waves. One wave is from L2S3 to L2S4, L2S5, L2S6, L2S7 and L2S8, and the other wave is from L2S3 to L2S2, L2S1. Both waves

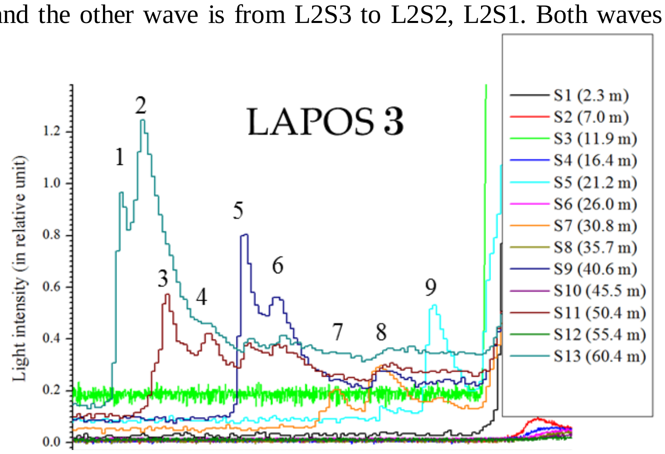

Fig. 3. L ight signal waveforms of the 6th leader of UF 14-11 recorded by LAPOS 3.

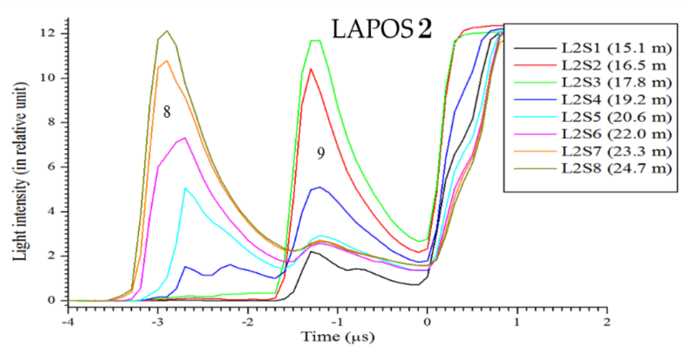

Fig. 2. Light signal waveforms of the pulse 8 and 9 in Fig. 2.

have attenuated sharply over a time period of 0.5 µs. The upward wave exhibited a speed of about 2.3×10^7 m/s. In contrast, the downward wave speed is about 1.4×10^7 m/s.

Figure 4 shows the light signals primarily from 5 channel sections of the 4th dart-stepped leader of UF 14-11 that occurred at 20:49:57, 21/06/2014 and were recorded by LAPOS 3. Similar to the leader shown in Fig. 2, a total of 9 light pulses occurred over the vertical range of about 40 m from S13 to S5

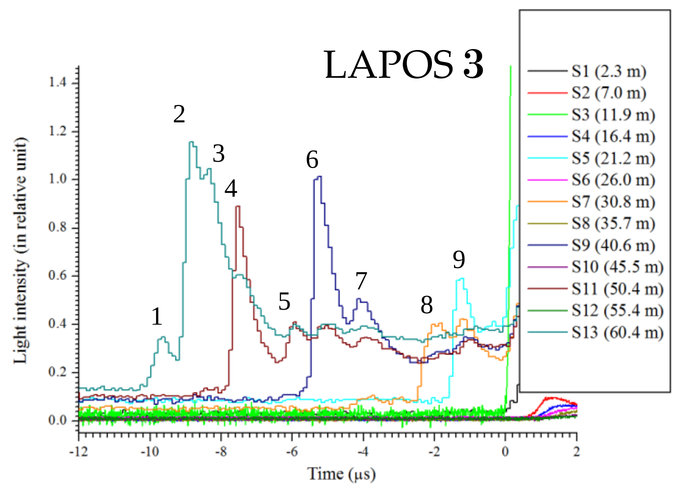

Fig. 5. Light signal waveforms of the 4th leader of UF 14-11 recorded by LAPOS

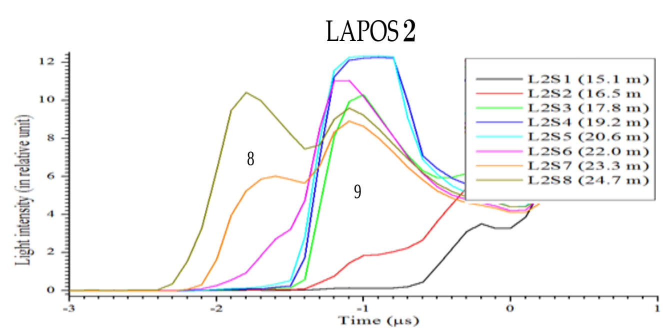

Fig. 4. Light signal waveforms of the pulse 8 and 9 in Fig. 4.

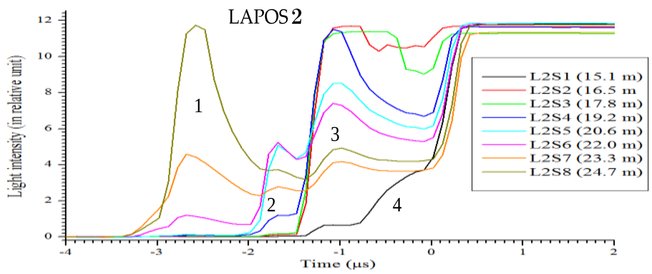

Fig. 7. Light signals of the 2nd leader of UF 14-35 recorded by LAPOS 2.

with a time interval of 8.5 μs. The resultant average leader speed is about 4.7×10^6 m/s. Figure 5 shows LAPOS 2 recording of the last two leader pulses 8 and 9 in Fig. 4. Pulse 8 propagated downward from L2S8 to L2S6 at a speed of about 5.4×10^6 m/s. Pulse 9 initiated at L2S5 and then propagated in bi-directional waves. One wave is from L2S5 to L2S6, L2S7, and L2S8, and the other wave is from L2S5 to L2S4, L2S3, and L2S2. The propagation speeds of the upward wave and the downward wave of Pulse 9 are about 2.7×10^7 m/s and 1.4×10^7 m/s, respectively.

Figure 6 shows the light signals of the 2nd leader of UF 14-35 recorded by LAPOS 2. Four pulses can be identified in Fig. 6 and are labeled as 1, 2, 3, and 4, respectively. Pulse 1 propagated downward from L2S8 to L2S5. Pulses 2 initiated at L2S4 and propagated in bi-directional waves. The upward wave of Pulse 2 is from L2S4 to L2S8, and the downward wave is from L2S4 to L2S3. Pulse 3 started at L2S3 and also propagated in bi-directional waves. The upward wave of Pulse 3 is from L2S3 to L2S8, and the downward wave is from L2S3 to L2S1. Pulse 4 can only be seen in L2S1. The downward propagation speed of Pulse 1 is estimated to be 2.1×10^7 m/s. The speeds of Pulse 2 upward and downward waves are 3.7×10^7 m/s and 1.2×10^7 m/s, respectively. The speeds of Pulse 3 upward and downward waves are 6.9×10^7 m/s and 2.3×10^7 m/s, respectively.

Figure 7 shows the light signals of the 4th leader of UF 14-52 recorded by LAPOS 2. Four pulses can be identified in Fig. 7 and are labeled as 1, 2, 3, and 4, respectively. Pulse 1 propagated downward from L2S8 to L2S7. Pulses 2 initiated around L2S6 and propagated in bi-directional waves. The upward wave of Pulse 2 is from L2S6 to L2S7, and the downward wave is from L2S6 to L2S5. Pulse 3 started at L2S4 and also propagated in bi-directional waves. The upward wave of Pulse 3 is from L2S4 to L2S8, and the downward wave is from L2S4 to L2S3. Pulse 4 initiated at L2S2 and also propagated in bi-directional waves. The upward wave of Pulse 4 is from L2S2 to L2S8, and the downward wave is from L2S2 to L2S1. For this leader, we are only able to estimate the propagation speeds for Pulses 3 and 4. The speeds of Pulse 3 upward and downward waves are 6.1×10^7 m/s and 2.8×10^7 m/s, respectively. The speeds of Pulse 4 upward and downward waves are 4.1×10^7 m/s and 1.4×10^7 m/s, respectively.

IV. Discussion and Summary

Although the data presented are limited, the results indicate that all the pulse discharges occurred at the tip of a dart stepped leader is a type of bi-directional discharges. For Pulse 8 in Fig.

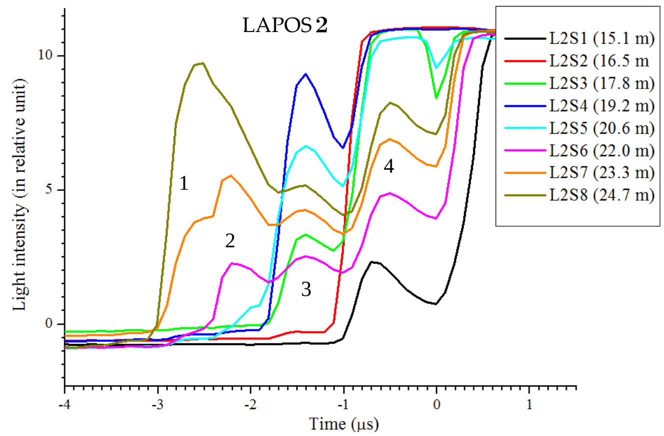

Fig. 6. Light signals of the 4th leader of UF 14-52 recorded by LAPOS 2.

3, Pulse 8 in Fig. 5, Pulse 1 in Fig. 6 and pulse 1 in Fig. 7, the limited view of LAPOS 2 only see part of their downward propagation waves. The speeds in both directions are at the order of 10^7 m/s. But the upward speeds appear always larger than their downward counterparts. For the downward propagation, it appears that there is a slowdown process as seen in Fig. 3 and Fig. 5. The downward speeds measured at the later stages are of the order of 10^6 m/s.

The downward discharges are generally weaker and propagate a shorter distance than the upward discharges. According to our estimation, the downward propagation distances of the pulse discharges are at most a few meters.

The progression of the dart stepped leader pulses of rocket triggered lightning has been previously measured by Wang et al. [1999]. Since the spatial resolution of their equipment was about 30 m, apparently they could not observe the downward part of the pulse discharge. The pulse upward speeds observed by Wang et al. [1999] appear larger than in this study. Since the height range viewed by Wang et al. [1999] is more than 10 times wider than this study, perhaps this suggests that there could be some acceleration in the upward propagation of the pulse discharge as in the cases of return strokes observed by Olsen et al. [2004].

Interestingly, all the bi-directional discharges initiated at a location immediately below where the downward part of its previous bi-directional discharge reached. There should be stems and space leaders further below the pulse initiation locations, but apparently LAPOS 2 was not sensitive enough to record them. As seen in Fig. 6 and Fig. 7, the time intervals between some adjacent two pulse discharges could be less than 1 μs. These pulse discharges may be produced due to simultaneous multiple stems observed by Gamerota et al. [2014].

Acknowledgment

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