



Bidirectional development of dart leader observed in pre-existing channel

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Abstract— Bidirectional development of dart leader propagating through pre-existing channel was observed in a high structure-initiated upward negative flash and a rocket-triggered flash by high-speed camera. The dart leader in the structure-initiated flash initially propagated downward through the upper channel with decreasing speed and luminosity, and terminated at an altitude of about 2200 m. It restarted subsequently its development at the terminated position with both upward and downward channel extensions. The average 2D speed of upward positive end was 5.3×10^6 m/s, while that of the downward negative end was 2.2×10^6 m/s. For the rocket-triggered lightning with 6 leader-stroke sequences, only its first dart leader exhibited bidirectional development. The dart leader started suddenly at an altitude of about 452 m, without obvious detectable downward propagation from cloud. The average 2D speed of upward positive and downward negative leader was 1.3×10^6 m/s and 7.8×10^5 m/s, respectively. The results show that the old dying channel remnant can survive as a floating nucleus and induce bidirectional propagating leaders.

Keywords- Bidirectional propagation; dart leader; speed; high structure-initiated flash; rocket-triggered flash

I. INTRODUCTION

A fundamental concept of a bidirectional lightning leader was proposed firstly by Kasemir [1] in 1960. This model indicates that the lightning leaders breakdown virgin air extend in opposite directions, forming the channel structure of double-ended trees[2]. This concept has been verified by various means of observation. Laboratory long sparks showed that streamers initiated from two ends of a suspended conductor in the applied electric field [3]. The lightning striking to the aircraft exhibited bi-directional leader breakdown from the upper and lower portions of the aircraft [4], and the similar behavior was found in altitude triggered lightning [5][6]. Recently, Montanyà [7] presented evidence of bidirectional lightning initiation with virgin bidirectional leader development.

Dart leader in negative cloud-to-ground (CG) lightning develops in a pre-conditioned channel traversed by the

preceding return stroke, and usually propagates in continuous manner with little or no branching and involve considerably faster speed than stepped leaders [8][9][10], although some dart leaders may transform into dart-stepped ones and exhibit stepwise development as the existing channel decayed and the conductivity became poorer [11][12]. Most of the optical studies on dart leaders concentrated on the properties of their downward propagation, for the upper portion of the discharge channel in CG flashes were usually obscured by the cloud, and hence, could hardly be captured by optical means. To date, the initial propagation of the dart leaders are still rarely investigated. In this paper, dart leaders in an upward negative CG flash initiated from a high structure and a rocket-triggered CG flash were studied in detail mainly on basis of the high-speed images, and a bidirectional development of dart leader propagating through pre-conditioned channel was clearly observed.

II. INSTRUMENTATION AND OBSERVATION

A Photron Fastcam SA1 high-speed digital video camera configured with a Nikon 24-85 mm lens at f/2.8 was used in the high-structure initiated lightning observation. The camera was located at 9th floor of IAP (Institute of Atmospheric Physics) 40# building in Beijing, and it was operated at a frame rate of 10,000 fps with a spatial resolution of 1024×528 pixels. An upward CG flash initiated from a tall structure located 8 km away from the camera was captured at 12:43:33 (UTC), May 19, 2012.

A Phantom V711 high-speed camera was employed in rocket-triggered lightning. The camera was equipped with Nikon 14 mm focal length lens, operating at 25,000 fps with spatial resolution of 512×512 pixels. Video data from camera was synchronized with other data by GPS. The rocket-triggered lightning flash with six return strokes was observed at 04:17:18 UT, on 18 August 2014, in Shandong province.

III. ANALYSIS AND RESULTS

A. The high structure-initiated flash

Figure 1 shows the composited high-speed images of the main channel of the structure-initiated lightning flash. Based on the electric field measurement, the flash was of negative

polarity which initiated as upward positive leader and eventually lowered negative charge from cloud to ground. The upward positive leader originated at the area of "A" with the exact origination point being not exactly known, due to the view obstruction by a higher building between the camera and the lightning-involved object. As shown in Figure 1, the upward positive leader branched during its propagation toward the cloud. During the upward leader development and the resultant initial continuous current, frequent recoil leaders occurred (not illustrated in the figure) in the branches, propagating backward to the trunk-channels, which were normally observed during the initial stage of the upward negative lightning flash [13][14]. The initial stage of this flash lasted 251 ms, and then the luminous channel became extinguished, indicating a current cut off of the channel. After that, several leader processes intermittently occurred in different channel remnants with obvious re-illumination of the channel. Most of these leaders died out within a short time and failed to propagate lower to reach the origination area of "A", and hence, did not induce a return stroke (as generally termed attempted leaders). There were two dart leaders succeeded in reaching the channel origination and eventually induced return strokes. Both these two leaders exhibited similar bidirectional features and the second one is selected for detailed presentation in the following section.

Figure 2 shows the development of the bidirectional dart leader that propagated through the channel remnant marked with dashed lines in Figure 1. The time interval between this dart leader and the preceding attempted leader occurred in the same channel was 56 ms. As shown in Figure 2, this negative polarity leader initially exhibited a unique downward propagation, with the channel luminosity gradually weakened, indicating a decaying of the leader development. The luminous channel of the leader gradually shortened in length and eventually terminated at the point of P1 with an altitude of about 2200 m. At the time of frame 0, only two tiny segments with very weak luminosity can be identified in the channel. They were separately located at P1 and P2. Then, as shown in the following frames, the dart leader restarted to develop and evidently exhibited both upward and downward channel extension. The downward portion of the leader continued to progress in the channel remnant that was produced by the initial upward positive leader, while the upward portion retraced the route that was just traversed by the decaying leader development. Finally, the downward development of the leader reached the origination area of this upward lightning flash and induced a return stroke that followed with continuing current of 103 ms duration.

Figure 3 shows the 2-D partial speeds evolution of the bidirectional dart leader, including both downward and upward propagation. The relative luminosity of the channel is also plotted in the figure. As shown in the figure, the downward decaying leader that developed in the upper portion of the channel (as indicated by the red dashed line in Figure 1) involved a 2-D partial speed of about 10^7 m/s when it was initially captured in the top right corner of the camera field of view. Then the leader exhibited significant decreasing partial speed, accompanied with the weakening channel luminosity.

The speed value of "zero" corresponds to the terminating of the downward leader propagation at the point of P1 (as illustrated in Figure 2). Along with the restart of the leader with bidirectional propagation, the 2-D partial speed exhibited increasing tendency, both for the upward and downward extension of the leader channel, accompanied with the strengthening channel luminosity. The partial speed for the upward propagation of the bidirectional leader was $0.32-1.1 \times 10^7$ m/s, with an average speed of 5.3×10^6 m/s. While for the downward propagation, the partial speed was $1.0-3.2 \times 10^6$ m/s, with an average speed of 2.2×10^6 m/s.

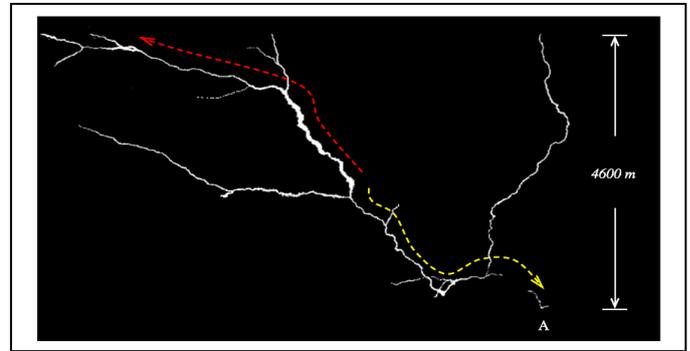


Figure 1. Integrated high-speed image showing the main channel structure of the object-initiated lightning. The channels were formed by the upward positive leader that initiated at the area of "A" and branched as it propagated upward. The concerned bidirectional dart leader developed through the channel remnant (indicated by the dashed lines) after the upward leader extinguished. (Adopted from [15])

Figure 2. Image with arranged consecutive frames revealing the dart leader development. Note that the image color is inverted for a better presentation. The leader propagated through the channel marked with the dashed lines in

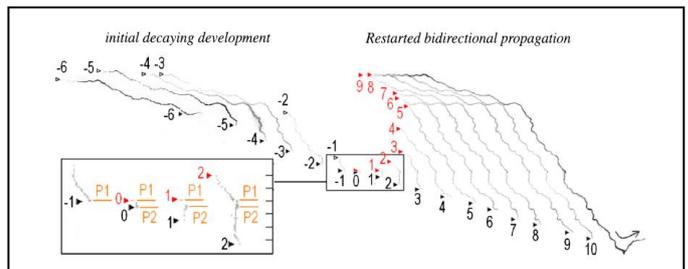


Figure 1. The frame number of "0" indicates the termination of the decaying downward leader and then the restart of the leader with bidirectional development. (Adopted from [15])

It is inferred that the upward portion of the bidirectional leader was of positive polarity while the downward portion was of negative polarity based on the already determined negative polarity of the flash. Since the upper portion of the channel was previously traversed by a decaying downward negative leader process which theoretically lowered negative charge to the channel, we tend to consider that the whole channel extension due to the following bidirectional development of the dart leader did not involve zero net charge. In the expanded view of frames -1~2 in Figure 2, the initiation of the downward channel extension with negative polarity was prior to the upward extension with positive polarity. This behavior is different from

those conductor-involved bidirectional leaders, such as the laboratory long sparks and the initial leader development of the altitude-triggered flashes, which exhibited earlier initiation of the positive leader or positive streamer [3].

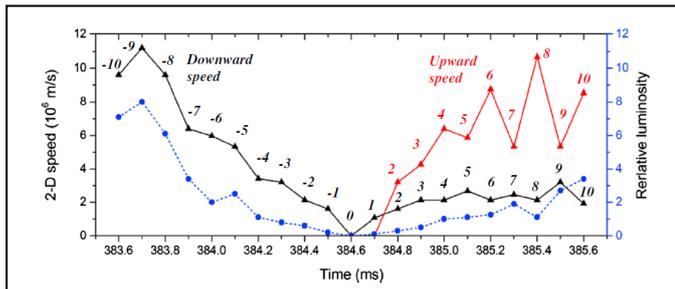


Figure 3. The 2-D partial speeds evolution of the bidirectional dart leader. The marked number corresponds to the frame number shown in Figure 2 and the labeled time was related to the initiation of the upward lightning flash. The time-correlated relative luminosity of the channel is also shown in the figure. (Adopted from [15])

B. The rocket-triggered lightning flash

The rocket-triggered lightning flash contained six leader-return strokes sequences, and the entire flash lasted about 620 ms. After checked all the imaged carefully, it is found that only the first dart leader (DL1) exhibited bidirectional propagation. Figure 1 shows the selected consecutive video frames of the first dart leader preceding the first subsequent return stroke. All these frames are contrast enhanced to the same extent to better show the faint luminous of the channel. Time progresses from left to right, and the whole visible channel spans 660 m in altitude. The dashed lines of blue color in the figure indicate the propagation tendency of the leader. Conspicuous bidirectional propagation of DL1 was observed in Figure 1. A total of 13 frames, labeled with numbers in order, are observed for DL1. In Figure 1-1, the whole channel was dark and blurry like that in previous frames (not shown), with only low-level luminosity through the wire channel remnant, indicating little current in the channel with very low conductivity. Then in Figure 1-2, the position, pointed by the blue arrow, got brighter. Further, in the next frame, a conspicuous bright point become visible at about 517 m altitude, as shown in Figure 1-3. Then, the leader tip became dark and kept invisible from Figure 1-4 to Figure 1-6. After that, the leader appeared suddenly at point 'x', marked with a blue arrow in Figure 1-7, at about 452.3 m altitude, referring time zero. Then the DL1 developed bidirectionally with one end traversed back to the high altitude along the old upper channel, while the other end continued to propagate downward. From Figure 1-8 to 1-13, the whole channel's luminosity increased with time. The RS1 occurred in Figure 1-14, and the pixels in the frame were saturated. In the last two frames before RS1, the lower channel was brighter than the upper channel.

The 2-D speed of both leader ends are shown in Figure 5. It shows that the positive upward leader in DL1 propagated faster than the downward negative leader until the upward leader propagated outside the field view of the camera. The upper positive leader exhibited partial speed ranging from 1.1-

1.6×10^6 m/s with an average speed of 1.3×10^6 m/s over 0.16 ms. The downward leader seemed to accelerate as it approaching to ground and its speed ranged between 0.6 - 2.4×10^6 m/s with an average value of 7.8×10^5 m/s over the first 0.16 ms and 1.2×10^6 m/s over the whole 0.24 ms.

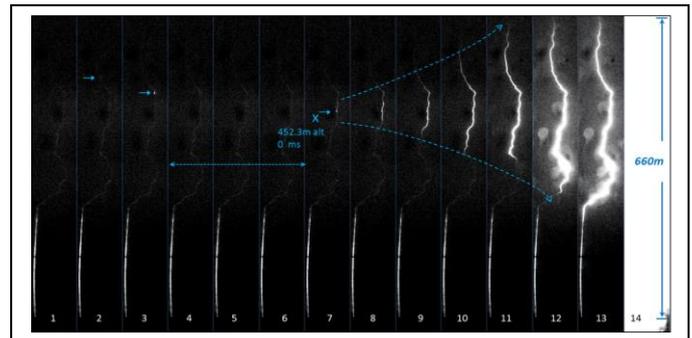


Figure 4. Selected sequential video frames of dart leader (DL1) preceding the first return stroke (RS1) of triggered flash at 04:17:18 UT, 18 August 2014. Blue dashed arrow outlines the leader's propagation tendency. Arrow labeled with 'x' indicates the start position of bidirectional propagation. All frames are contrast enhanced. The time interval between consecutive frames is 40 μ s, with 17.0 μ s exposure time per frame

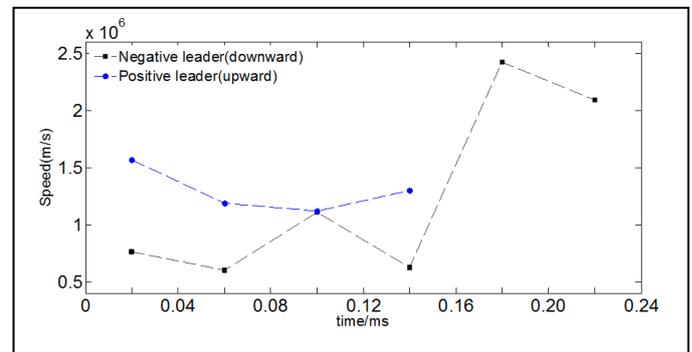


Figure 5. Estimated 2-D speed of the positive upward leader end and the negative downward leader end.

TABLE I. THE ESTIMATED DART LEADER 2-D SPEED

	<i>Time visible (ms)</i>	<i>First visible altitude (m)</i>	<i>Average 2-D speed (m/s)</i>
DL1 upward positive branch	0.24	452.3	1.3×10^6
DL1 negative downward branch	0.24	452.3	1.2×10^6
DL2	0.20	541	2.3×10^6
DL3	0.04	369.9	$>1.0 \times 10^7$
DL4	0.08	492.8	6.7×10^6
DL5	0.08	534	1.2×10^7
DL6	0.04	344	$>9.8 \times 10^6$

Development of the 3th and 6th dart leader (DL3, DL6) is too fast to be distinguished accurately, and a minimum value is estimated. The altitude here is the vertical distance from top of the 5 m high lightning rod served to attract lightning to the current detecting devices.

Table 1 shows the estimated 2-D speed for all the six dart leaders. The DL2 propagated down to the ground continuously at an estimated 2-D average speed of 2.3×10^6 m/s over 0.20 ms, faster than the speed of both ends of DL1. After RS2, Other four subsequent return strokes with similar dart leaders occurred. The luminosity of the later 4 dart leaders was much more intensive than that of the DL1 and DL2. It is difficult to distinguish the leaders' borderlines since pixels close to the channel are all saturated in video images. The latter 4 dart leaders propagated at a higher 2-D speed. The 2-D speed of DL4 and DL5, around 6.7×10^6 m/s and 1.2×10^7 m/s, respectively, is poorly estimated through just two consecutive frames over one interval (40 μ s). The 2-D speed of DL3 and DL6 is estimated to be faster than 1.0×10^7 m/s and 9.8×10^6 m/s, respectively.

IV. CONCLUSION AND DISCUSSION

The dart leaders showing bidirectional propagating are analyzed based mainly on high-speed images for an upward negative CG lightning flash that initiated from a high structure and a rocket triggered flash. The structure initiated flash incepted in the form of upward positive leader that branched during its propagation toward the charged cloud, while the triggered lightning initiated from an upward positive leader for the tip of the rocket.

For the structure-initiated flash, the dart leader initially propagated downward through the upper channel with decreasing speed and luminosity, and terminated at an altitude of about 2200 m. It restarted subsequently its development at the terminated position with both upward and downward channel extensions. The dart leader in the structure-initiated flash initially propagated downward through the upper channel during which period it decayed with decreasing luminosity and speed, and then terminated at its midway. It restarted subsequently its development at the terminated position with both upward and downward channel extensions. The average 2D speed of upward positive end was 5.3×10^6 m/s, while that of the downward negative end was 2.2×10^6 m/s. For the rocket-triggered lightning with 6 leader-stroke sequences, only its first dart leader exhibited bidirectional development. The dart leader started suddenly at an altitude of about 452 m, without obvious detectable downward propagation from cloud. The average 2D speed of upward positive and downward negative leader was 1.3×10^6 m/s and 7.8×10^5 m/s, respectively.

Different from the bidirectional leader development in virgin air, the concerning bidirectional dart leader in both cases initiated and developed through a pre-existing channel that was firstly formed by the upward positive leader. The upward propagation of the positive leader exhibited 2-D partial speed larger than the downward negative leader. The faster development of the upward propagation with positive polarity may be due to the previous decaying downward leader development at the upper channel, which resulted in better channel condition and deposited negative charge in the channel, facilitating an easier progression for the upward portion of the bidirectional leader system than its downward progression.

In the case of structure-initiated flash, the bidirectional propagation of dart leader seems related to its remarkable weakening of the initial downward dart leader when it propagated toward ground. The dart leader from the cloud propagated in a decreasing speed with weak luminosity, and it died out in the air when the potential at the tip can't support its self-sustaining propagation. For the rocket-triggered lightning case, the downward leader from the cloud was not clearly detected. All the results suggest that the old dying dart leader tip or channel remnant could survive as a floating nucleus immersed in an electric field, and bidirectional propagating leaders initiated from its two ends, and induced return stroke finally.

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