High-speed video evidence of a dart leader with bidirectional development

Rubin Jiang1,2, Zhijun Wu1,3, Xiushu Qie1,2, Dongfang Wang1,3, and Mingyuan Liu1

1Key Laboratory of Middle Atmosphere and Global Environment Observation, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China, 2Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science and Technology, Nanjing, China, 3College of Earth Science, University of Chinese Academy of Sciences, Beijing, China

Abstract An upward negative cloud-to-ground lightning flash initiated from a high structure was detected by a high-speed camera operated at 10,000 fps, together with the coordinated measurement of electric field changes. Bidirectional propagation of a dart leader developing through the preconditioned channel was observed for the first time by optical means. The leader initially propagated downward through the upper channel with decreasing luminosity and speed and terminated at an altitude of about 2200 m. Subsequently, it restarted the development with both upward and downward channel extensions. The 2-D partial speed of the leader's upward propagation with positive polarity ranged between $3.2 \times 10^6$ m/s and $1.1 \times 10^7$ m/s with an average value of $6.4 \times 10^6$ m/s, while the speeds of the downward propagation with negative polarity ranged between $1.0$ and $3.2 \times 10^6$ m/s with an average value of $2.2 \times 10^6$ m/s. The downward propagation of the bidirectional leader eventually reached the ground and induced a subsequent return stroke.

1. Introduction

A fundamental concept of bipolar development of lightning channel first proposed by Kasemir [1960] indicates that the lightning leaders breaking down virgin air extend in opposite directions, forming the channel structure of double-ended trees [Williams, 2006]. Based on this concept, positive and negative charges are considered to separately deposit in each side of the channel with same magnitude, which means a zero net charge in the whole channel [Mansell et al., 2002; Vargas and Torres, 2008]. Such an important 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 [Castellani et al., 1998]. The lightning striking to the aircraft exhibited bidirectional leader breakdown from the upper and lower portions of the aircraft [Mazur, 1989], and similar behavior occurred in the altitude-triggered lightning [Lalonde et al., 1998; Chen et al., 2003].

In negative cloud-to-ground (CG) lightning, as contrast with the stepped leaders breaking down virgin air, subsequent leaders developed in the preconditioned channel traversed by the preceding return stroke (or by the upward leader in object-initiated CG lightning). On streaking camera photos, they exhibited brightest luminosity at the tip with tens of meters length and hence were termed as dart leaders [Uman, 2001]. Dart leaders generally propagate in continuous manner with little or no branching and involve considerably faster speed ($10^6$–$10^7$ m/s) than stepped leaders (about $10^5$ m/s) [Jordan et al., 1992; Wang et al., 1999; Qie and Kong, 2007]. Some dart leaders may transform into dart-stepped ones and exhibit stepwise development as the existing channel decayed and the conductivity became poorer [Orville and Idone, 1982; Rakov and Uman, 2003; Petersen and Beasley, 2013]. Since the upper portion of the discharge channel in CG flashes were usually obscured by the cloud, the propagation properties of dart leader during its initial development could hardly be captured by optical means and hence were not well understood. To date, the detailed investigation about this issue is still rare.

In this paper, a dart leader in an upward negative CG flash that initiated from a high structure was studied in detail mainly on basis of the high-speed images. Evident bidirectional propagation of the dart leader documented by direct optical means with fine time resolution is reported for the first time.

2. Instrumentation and Observation

The high-speed images used in this study were captured by a Photron Fastcam SA1 high-speed digital video camera configured with a Nikon 24–85 mm lens at f/2.8. The camera was located at ninth floor of IAP...
(Institute of Atmospheric Physics) 40# building in Beijing, China, and it was operated at a frame rate of 10,000 fps with a spatial resolution of 1024 × 528 pixels. Fast and slow antennas with upper frequencies of 5 MHz and 2 MHz, and time constants of 1 ms and 3 s, respectively, were installed at the roof (11th floor) of the IAP 40# building to detect the electric field changes caused by the lightning discharges.

The observed upward CG flash occurred at 12:43:33 (UTC), 19 May 2012. It initiated from a tall structure that located 8 km away from the camera. At such a distance, a single pixel stands for a spatial area of 10.8 × 10.8 m².

3. Analysis and Results

Figure 1 shows the composited high-speed image of 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 curves) after the upward leader extinguished.

Figure 1. Composited high-speed video 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 curves) after the upward leader extinguished.

Based on the electric field measurement, the flash was of negative polarity which initiated in the form of 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 clearly 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 (IS) of the upward negative lightning flash [Warner, 2012; Jiang et al., 2014]. The initial stage of this flash lasted 251 ms, and then the luminous channel became extinguished, indicating a current cutoff of the channel. After that, several leader processes intermittently occurred in different channel remnants with obvious reillumination 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 figure was composed of arranged consecutive frames with an inverted color from the high-speed video images. The time interval between this dart leader and the preceding attempted leader that occurred in the same channel was 56 ms, the preceding attempted leader terminated at an altitude of about 2400 m, which is 20 m higher than the bidirectional leader initiation as analyzed in the following section. As shown in Figure 2, the dart leader initially exhibited a unique downward
propagation (frame $-6$ to frame $-1$), with the channel luminosity gradually weakened, indicating a decaying of the leader development. As determined by the flash polarity discussed above, it is reasonable that the leader was of negative polarity. 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 examined 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 (as termed A in Figure 1) and induced a return stroke, as confirmed by the continuing current which lasted about 102 ms, with the channel exhibiting sustained luminosity. It is interesting that after the considered grounding occurred, the channel exhibited considerably weaker luminosity than normally observed and the relative E-field magnitude was small either, implying a very weak return stroke. Figure 3 shows the 2-D partial speed evolution of the bidirectional dart leader, including both the downward propagation and the upward propagation. The average luminosity of the channel with relative value 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 2-D partial speed of about $10^7$ m/s when it was initially captured in the top left corner of the camera field of view, ranging between $1.6 \times 10^6$ m/s and $1.1 \times 10^7$ m/s with an average speed of $5.9 \times 10^6$ m/s. 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

**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.

**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 average luminosity of the channel (with relative value of the whole luminous channel) is also shown in the figure.
partial speed exhibited increasing tendency, both for the upward extension and downward extension of the leader channel, accompanied with the strengthening channel luminosity. The partial speed range for the upward propagation of the bidirectional leader was $3.2 \times 10^6$ m/s to $1.1 \times 10^7$ m/s, with an average speed of $6.4 \times 10^6$ m/s. While for the downward propagation, the partial speed range was $1.0 \times 10^5$ m/s to $3.2 \times 10^6$ m/s, with an average speed of $2.2 \times 10^5$ m/s.

As inferred by the already determined negative polarity of the flash, it is reasonable that the upward portion of the bidirectional leader was of positive polarity while the downward portion was of negative polarity. Based on the “zero net charge” concept of the bidirectional leader breaking down virgin air, positive and negative charges are separately deposited in the opposite ends of the channel. In this study, 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 $-1$ to $2$ 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 [Castellani et al., 1998].

4. Discussion

Since the optical observation of dart leader at the upper channel was still rare, it is not sure whether the bidirectional propagation observed in this study is a common phenomenon or just a particular anomaly. Nevertheless, the interesting images here did confirm the bidirectional concept of lightning to be also applicable for the leader development with long propagation through the preconditioned channel. It is clear in Figure 3 that the progressing speed of the leader’s upward propagation with positive polarity was larger than that of the downward propagation with negative polarity. Since the research on positive leaders are still rare, statistical comparison between the propagation of positive leaders developing through preconditioned channels and that of negative leaders (subsequent ones) still could be hardly conducted to date. Jerauld et al. [2004] once observed a bipolar-triggered lightning flash, and based on the field measurements, they estimated the speed of the positive dart leader to be $0.7 \times 10^7$ m/s, which is consistent with the speed for the upward propagation of the bidirectional leader in this study. Wang and Takagi [2013] recently documented two positive dart leaders occurring in a prechanneled upward negative lightning flash, with the propagation speeds estimated to be around $3 \times 10^7$ m/s, considerably larger than the positive developing portion of the leader here. For a further examination of faster development at the positive portion of this bidirectional leader than the negative portion, it may be possible that the reduced pressure or hydrometeors at altitude may had conducted influence. Meanwhile, it may also be related to the previous decaying downward leader development in the upper channel. Such development resulted in a better condition (higher channel temperature and better conductivity) of the upper channel than the lower channel, which facilitated an easier progression for the upward portion of the bidirectional leader than its downward progression. Furthermore, although the previous decaying leader eventually terminated, there should be residual negative charge deposited in the channel, and this may also promote the bidirectional leader’s upward propagation with positive polarity.

As further illustrated in Figure 3, the variation tendency of partial speed for the leader’s upward propagation was to a certain extent inversely related to that for the downward propagation. From frame 3 to frame 10, the increasing speed of the upward propagation was time-correlated with the decreasing speed of the downward propagation. This behavior seems to imply that there was an interaction between the channel extensions in the opposite directions. Considering the energy for supporting the leader progression as a whole, the enhancement of the leader development at a certain direction possibly had conducted limiting effect on the development at the opposite direction. Nevertheless, this inference is not quite sure, since the leader propagation may be influenced by local conditions such as pressure and hydrometeors. For a further and more detailed discussion of this issue, additional observations are needed.
5. Conclusion

In this study, we analyzed in detail the high-speed images of an upward negative CG lightning flash that initiated from a high structure. The flash incepted in the form of upward positive leader that branched during its propagation toward the charged cloud, with an IS (initial stage) duration of 251 ms. The concerning bidirectional dart leader developed through a preconditioned channel that was first formed by the upward positive leader. The leader initially propagated downward through the upper channel during which period it decayed with decreasing luminosity and speed and then terminated at a point with altitude of about 2200 m. After that, the high-speed images revealed a bidirectional channel extension due to the restart of the leader. The upward propagation of the leader exhibited the 2-D partial speed range of $3.2 \times 10^5$ m/s to $1.1 \times 10^7$ m/s, with the average speed being $6.4 \times 10^4$ m/s, while the speed of the leader’s downward propagation ranged between 1.0 and $3.2 \times 10^4$ m/s, with the average speed of $2.2 \times 10^4$ m/s. The faster development of the upward propagation with positive polarity may be due to the previous decaying downward leader development at the upper channel and the local conditions as well. The previous leader at the upper channel may have 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. Our result directly documented the bidirectional propagation of dart leader that retrace the preconditioned channel by optical means for the first time.

References


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