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Propagation of positive, negative, and recoil leaders in upward lightning flashes

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Abstract: Leader propagation is a fundamental issue in lightning physics. The propagation characteristics of positive leaders and negative leaders are summarized and compared based on data from high-speed camera and electromagnetic field in rocket-triggered lightning and tower-initiated lightning discharges; available channel base current data recorded in rocket-triggered lightning are also used. The negative leaders propagate in a stepped fashion accompanied by many branches. The stems ahead of the negative leader tip determine the manner and direction of the leader propagation, and even the branching and winding of the lightning channel. The impulsive current, electromagnetic field, and related optical images suggest that the positive leader may develop in a step-like fashion at its initial stage of triggered lightning. However, the stepping processes of the positive leader are obviously different from those of the negative leader. Tower-initiated lightning revealed that the most conspicuous characteristics of the stepwise positive leader involve the intermittent brush-like corona zone in front of the leader tip and the luminosity enhancement of the channel behind the tip. In rocket-triggered lightning flashes, the charge transferred during an individual step for the negative leader was nearly an order greater than for the positive counterpart. The successive streamers ahead of the leader tip are essential for both negative and positive leader propagation, and the stems could be formed from one or more streamers in the previous negative streamer zone with the main leader channel dim. High-resolution observation of tower lightning also revealed a new type of bidirectional recoil leader, with polarity contrary to the traditional one, traversing in negative channels associated with tower-initiated and rocket-triggered lightning.

Keywords: lightning propagation; negative leader; positive leader; recoil leader

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1. Introduction

The propagation of lightning leaders is one of the outstanding issues in the research of lightning physics. It is generally accepted that the negative leaders propagate in a stepped fashion, while the positive leaders extend continuously or exhibit optically unresolvable steps in lightning discharges or long sparks (e.g., Berger and Vogelsanger, 1966; Gorin et al., 1976; Gallimberti, 1979).

Gorin et al. (1976) found that the stepping processes of a negative leader in a laboratory spark discharge can be divided into three main processes: (i) appearance of a space stem, which moves forward in the streamer zone in front of the root leader tip; (ii) bidirectional development of the space stem, from which the positive streamer retraces back to the root leader tip and the negative streamer forward; (iii) connection and a new stepping process, in which the backward positive streamers well connect to the root negative leader tip, and a new leader channel segment forms; meanwhile, a burst of streamers is excited from the new leader tip and a new space stem is again produced. Recently, Kostinskiy et al. (2018) found both stepped and continuous positive leader progression in long sparks, and that larger steps can occur for a positive leader when the absolute humidity is high or the rise time of input voltage is longer.

Although different propagation features of negative and positive leaders in natural lightning were first revealed by early streak camera pictures (e.g., Berger and Vogelsanger, 1966), the progression processes could not be sufficiently resolved in detail due to the poor resolution. It was just in recent years that similar stepping processes featured as space stems in natural negative lightning leaders were captured by high-speed video cameras (HSV).

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Biagi et al. (2009) first observed a space stem with a 2 m length, 4 m below a downward propagating negative leader tip, in rocket-triggered lightning with HSV operating at 20 μs frame resolution. Existence of the space stem has been confirmed in many subsequent observations associated with negative lightning leaders (e.g., Biagi et al., 2014; Petersen and Beasley, 2013; Qi Q et al., 2016; Jiang RB et al., 2017). Gamerota et al. (2014) named the similar bidirectional development of stems "space leaders". These results well confirmed the similarities between negative leader step processes in natural lightning and those in long sparks. Qi Q et al. (2016) found that even multiple space leaders can coexist, and Jiang RB et al. (2017) found that successive or almost simultaneous connections of coexisting multiple space leaders to the same root negative leader tip resulted in both stepping and branching or zigzagging propagation of negative leaders.

The propagation features of natural lightning leaders are usually observed by optical observation in the later stage when the leader develops out of the cloud or even when it approaches the ground (e.g., Qie and Kong, 2007; Stolzenburg et al., 2015; Tran et al., 2014; Qi Q et al., 2016; Jiang RB et al., 2017). Because of cloud shielding, the initial processes of the positive and negative leaders have rarely been observed, resulting in poor understanding of their early propagation.

Upward natural lightning is usually initiated from tall towers or skyscrapers, with an upward positive leader (UPL) or occasionally upward negative leader (UNL). Rocket-triggered lightning with trailing wire technique experiences similar discharge processes to tower-initiated lightning, and both of them contain an initial upward propagating leader and an initial continuing current stage. In this paper, the formation processes of leader steps and branches are summarized and compared by using data from high-speed video and electromagnetic fields for rocket-triggered lightning and tower-initiated lightning discharges, and channel base current data recorded in rocket-triggered lightning. The function of the streamer zone in both negative and positive leaders will be highlighted. Also discussed will be a bidirectional recoil leader process, associated with tower-initiated and rocket-triggered lightning, which traverses negative channels, contrary to the traditional one in polarity.

2. Experiment and Data Description

The dataset is from rocket-triggered lightning in the SHAndong Triggering Lightning Experiment (SHATLE), which has been put into operation since 2005 at Binzhou, Shandong province. More than 70 negative flashes and 2 positive flashes have been triggered in the last decade (e.g., Qie XS and Kong XZ, 2007; Qie XS et al., 2017; Yang J et al., 2010, Jiang RB et al., 2013; Sun ZL et al., 2014; Pu YJ et al., 2017). The channel-base current was detected by a 5 mΩ shunt and a Pearson coil, and the dynamic range of the current measurement was from 10 A to 40 kA (e.g., Qie XS et al., 2007; Jiang RB et al., 2013; Fan YF et al., 2018). The current waveforms were documented by DL850 oscilloscopes with a sampling rate of 10 MS/s. Several high speed video cameras, such as Phantom V711, Phantom V1612, M 310 operating at frame rates varying from 10,000 to 90,000 fps were utilized to capture the progression of each lighting leader in high temporal and spatial resolution. The evolution of lightning channel luminosity was measured by a photodiodes array system (called LOTUS) with high time resolution, designed to obtain the integrated luminosity at 14 particular levels with an array of the avalanched photodiode (Pu YJ et al., 2017). The electric fields were detected using a so-called fast antenna with time constant of 0.1 ms and bandwidth of 1.5 kHz–2 MHz, and a slow antenna with an adjustable time constant from 0.2–1.0 ms and bandwidth of 10 Hz–1MHz, respectively (Qie XS et al., 2011; Pu YJ et al., 2017). The magnetic field was detected by a low-frequency sensor (Lu GP et al., 2014, 2016). The electromagnetic fields were measured at several distances from the discharge channel, varying from about 30 m to 1 km. All the recorded signals were synchronized through GPS clocks with time accuracy better than 25 ns.

Upward lightning initiated from the IAP 325-m tower in Beijing was recorded with high speed video camera of Phantom V711, which was installed on the 9th floor of the IAP experimental building, a distance of about 910 m from the tower. The fast antenna and slow antenna to measure the lightning electric field changes were located on the roof of the IAP experimental building (Wang ZC et al., 2016), as one station of the Beijing Lightning Network (Wang Y et al., 2016).

3. The Behavior of Steps and Branches in the Upward Negative Leader

Among all the rocket-triggered lightning flashes from 2005–2018, just two cases were of positive polarity initiated by an upward negative leader (UNL). Both flashes contained only initial continuing current without return strokes. The current durations of these two flashes were 90 ms and 75 ms, respectively. The peaks of initial continuing current for the two flashes were 442.7 A and 981.3 A, and the charges transferred were 1.6 C and 1.3 C, respectively. Both flashes showed similar pulse features in their initial current and electromagnetic field waveforms. Pu YJ et al. (2017) analyzed the two flashes in detail. Here we focus on just the initial propagation feature of the negative leader.

The channel-base current is shown in Figure 1, presenting the initial 400 μs of the UNL for flash 1501 after the leader appeared from the wire tip. Nine initial current pulses are labeled P1–P9. It is obvious that the time intervals and peak amplitudes of the current pulses decreased after P9. Meanwhile, the UNL began to branch. The peak values and the time intervals of the current pulses can be observed to decrease significantly when branching started. The negative leader branches at the later stage produced chaotic current waveforms. Pu YJ et al. (2017) identified two steps during P2 between Frames 1 and 2 and P5 between Frames 3 and 4, respectively. The step lengths were about 8 m and 4.9 m, and the charges transferred from pulses P2 and P5 were 420.9 μC and 457.5 μC, respectively.

The main channel of the UNL was determined through identifying the continuous current, as shown by the red arrow in Figure 1c. The two dimensional (2-D) partial velocity of the main leader propagation ranged from 0 to 4.5×10^5 m/s with an average value of 2.1×10^5 m/s, while the 2-D velocity for all branches ranged from 0 to 6.1×10^5 m/s, showing some slight increases with altitude. It

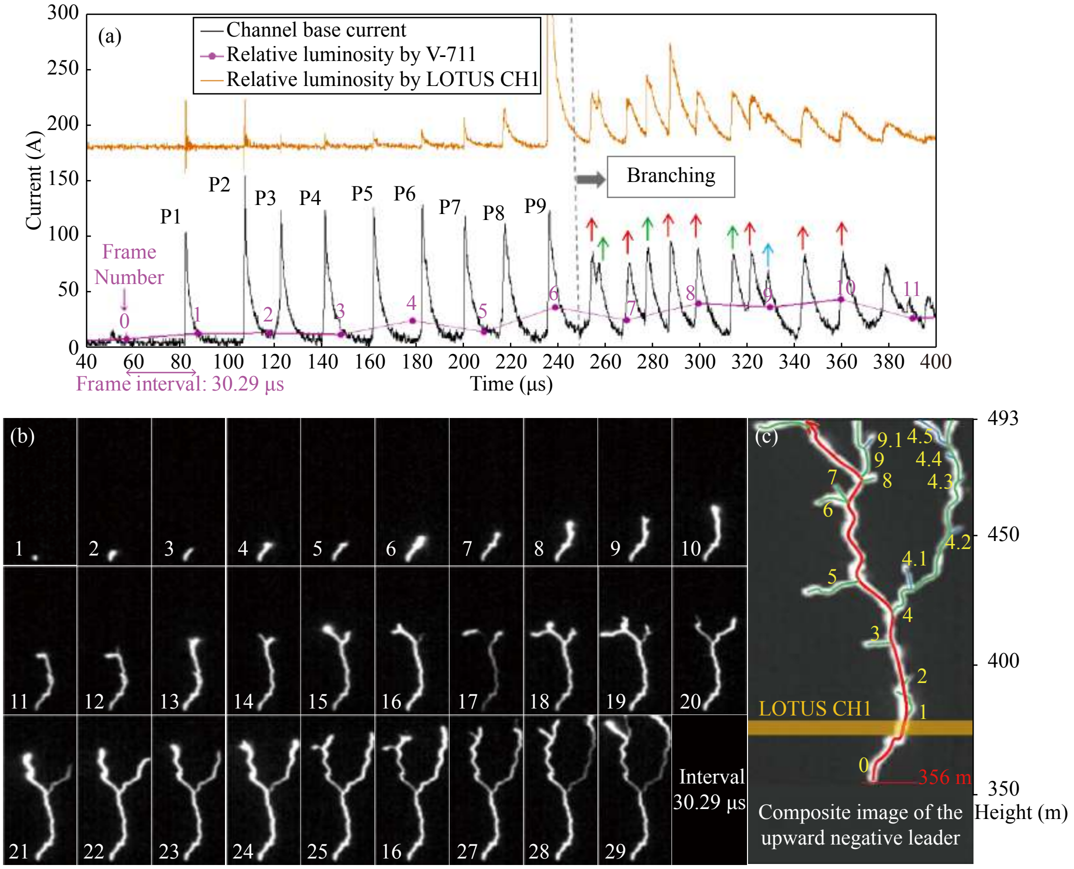

Figure 1. (a) Channel base current and simultaneously measured relative luminosity by high-speed camera and LOTUS at the very beginning for the upward negative leader of lightning 1501; (b) Consecutive images (interval of 30.29 µs); (c) Composite image from the video camera for the upward negative leader and illustration of the branches. The start position of the leader is at an altitude of 356 m and the red arrow denotes the main leader channel (Modified from Pu YJ et al., 2017).

should be mentioned that sometimes development of the main leader channel or branches could not be identified between two consecutive frames, causing zero speed values.

Figure 2 presents consecutive frames of a cloud-to-ground lightning discharge, showing obvious step-and-branch formation during a negative leader evolution. Jiang RB et al. (2017) used this figure to discuss negative leader branching and zigzagging. Here, we just refer to it to show the leader formation and the function of the streamer area associated with leader formation. In Frames 1 and 2, obvious bright areas in front of the leader tip indicate the formation of new steps. The luminous segments, as indicated by triangles in front of the leader tip, actually were the streamer zone and have been generally regarded as stems or space leaders in previous studies. Each separated luminous segment in Frame 2 became larger and brighter compared with Frame 1, indicating that the two segments developed bidirectionally with one end propagated backward to the main leader channel tip while a faint luminous end propagated forward; meanwhile, luminosity of the main leader channel became weaker, as shown on Frame 1 and Frame 2. When the illuminated segments connected to the main leader channel, the channel luminosity was enhanced, and a new leader step was accomplished with the leader channel extended forward a step. Then a new luminous segment ahead of the leader tip became a new streamer area, while the leader channel dimmed again, as shown in Frame 6. Based on statistical analysis of 96 steps, Jiang RB et al. (2017) found that the step-length geometric-mean value was 4.4 m (ranging from 1.3 to 8.6 m).

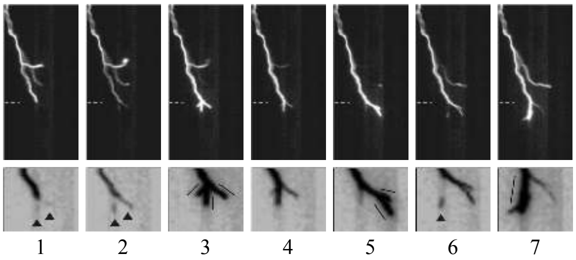

Figure 2. Consecutive frames, shown in inverted color, for a downward negative leader showing formation of leader steps and branches. The frames' temporal resolution is 5.56 µs with exposure time of 5.18 µs (Adapted from Jiang RB et al. (2014)).

It is interesting to note that the channel branch developed in a similar step fashion. In fact, the three bright segments shown on Frame 1 and Frame 6 in Figure 2 are indicative of short branches (as shown on the following frames) that eventually stopped their development. The three branches shown in Frame 3 were formed almost simultaneously. This indicates that a space leader or luminous streamers are essential for not only leader stepping, but also for leader branching and winding.

4. Stepwise Progression of Positive Upward Leader

The first 50 consecutive images, shown in Figure 3, present the initial progression of a UPL in a rocket-triggered negative lightning flash. It can be seen that a leader appeared from the wire tip at a height of about 130 m and showed a direction variation during the period. Few obvious leader branches can be observed in the camera's field of view, compared to the branching observed with negative leaders. The 2-D partial speed of the UPL were from 2.0×10^4 m/s to 1.8×10^5 m/s with an average speed of 1.0×10^5 m/s, which was much lower than seen with its negative counterpart.

Waveforms of channel base current and simultaneous electromagnetic field changes recorded for a rocket-triggered negative lightning discharge are shown in Figure 4. Current pulses similar to those of the UNL were identified from the very initial stage of the UPL, with peak currents of about several amperes to less than 100 A. Amplitudes of the current pulses decreased gradually and became imperceptible. The current pulses train was unipolar with a sharp peak, rise time of less than 1 μs, and the time interval was from 20–40 μs. These pulses indicate that the positive leader propagates in a clear intermittent manner in its initial stage.

These kinds of current and electromagnetic pulses have been observed in rocket-triggered lightning by several authors. Some of them have suggested that these pulses are a manifestation of a kind of stepping progression (e.g., Biagi et al., 2011; Jiang RB et al., 2013; Lu GP et al., 2014), and some of them have termed these pulses "precursors" (e.g., Willett et al., 1999; Lalande et al., 1998; Zhang Y et al., 2017). Lu GP et al. (2014) reported a long sequence of over 600 B-field pulses during the initial continuous current stage in a triggered-lightning discharge. The duration of these pulses was about 3–8 μs with a typical interval of about 30 μs. They attributed these pulses to step processes of positive leaders developed in thunderclouds. Lu GP et al. (2016) further divided these initial B-field pulses into impulsive pulses and ripple pulses based on their waveform characteristics. Both types of pulse had similar interpulse intervals, of about 25 μs. Considering all the observation facts, they suggested that both types of pulse shared a common generation mechanism of positive leader stepping. Fan YF et al. (2018) suggested that the impulsive pulses were produced during the processes of positive leader stepping, and that the impulsive current travelling downward along the prolonging higher impedance leader channel from the tip of the positive leader resulted in the impulsive current becoming rippled.

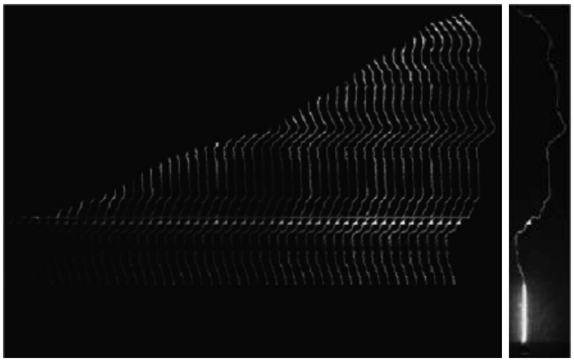

Figure 3. Images of an upward positive leader in triggered negative lightning, captured by a high-speed video camera at 10,000 fps. Left: First 50 images of the extending leader. Right: One frame of lightning channel with the lower bright straight part being the wire-affected channel with a height of about 130 m.

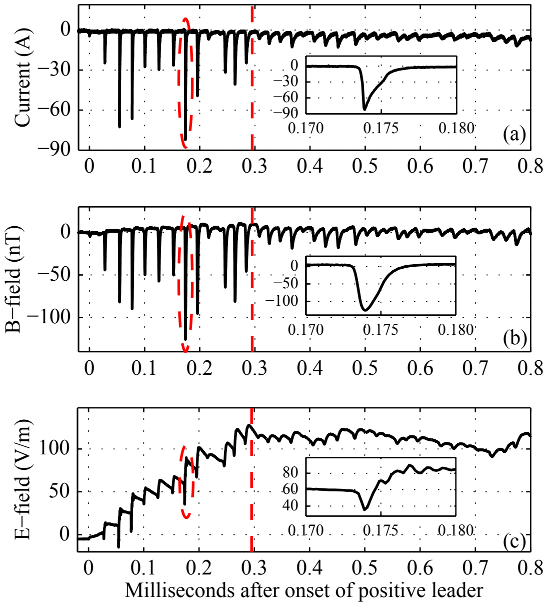

Figure 4. Waveforms of channel-base current, and electromagnetic field. (a) channel-base current, (b) B field, and (c) E-field change waveform immediately after onset of the upward positive leader. The red dashed lines mark the transformation between impulsive pulses and ripple pulses.

Based on rocket-triggered lightning, as mentioned above, we suggest that the progression fashion of the UPL could be intermittent or stepwise during the initial stage. The time interval between two adjacent current pulses or two steps was about 30 μs, and the length of an individual step, if any, was estimated to be in the range from 1 to 4 m (Jiang RB et al., 2013; Lu GP et al., 2014).

The stepping processes of an UPL from the IAP 325-m tower were detected by a high speed video camera located 910 m distant and working at a time resolution of 6.67 μs. Figure 5 presents 12 consecutive images showing the stepping processes of the UPL. The UPL did not exhibit obvious branches in the view of the camera. For a particular stepping process, as discussed by Wang ZC et al., (2016), the UPL tip first developed a brush-like bright area consisting of positive streamers (Figure 5b), then an abrupt jump forward with a brighter corona area (Figure 5c). The luminosity waves progressed toward the ground along the discharge channel from the leader tip immediately after the brightest corona stage, which marks a jump or a step of the leader tip. Then the leader tip dimmed gradually during Figures 5c–5i. Meanwhile, the leader tip was suspended for 7 consecutive frames. After that, the bright corona area was re-established, as shown in Figure 5j. Then the tip of the leader passed across the lower reference line to the upper line in the following frame, Figure 5k, and completed an accumulation of brush-like bright corona zones around the leader

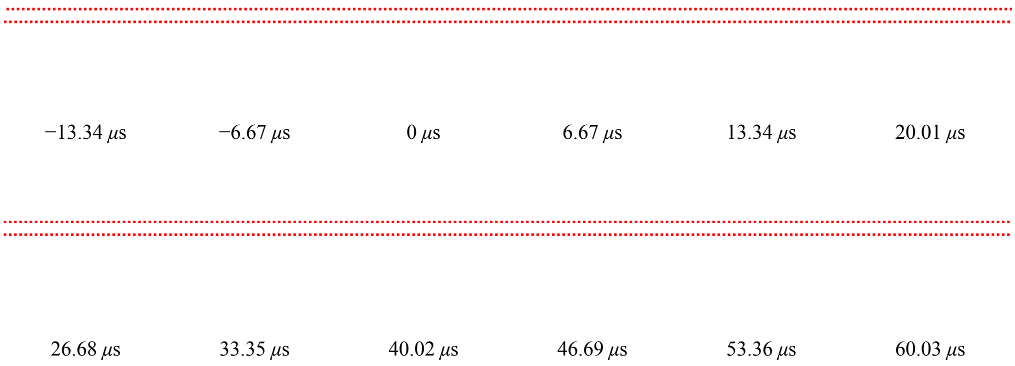

Figure 5. (a)–(l) Stepping processes of the upward positive leader, with image interval of 6.6 7 μs in 12 consecutive high-speed video images. The red dashed lines are used as the reference to illustrate the spatial development of upward positive leader top (Adopted from Wang ZC et al., 2016).

tip. The stepping process was repeated again from Figure 5l.

We conclude that the brush-like bright area played an essential role in the step-like progression of the positive leader. In the starting frames of the stepping, i.e., in Figures 5b and 5j, the bright areas appeared first at the top of the leader, indicating that the streamer discharges had started, followed by a full corona area and abrupt brightening of the discharge channel, shown in the following stepping frames, i.e., in Figures 5c and Figure 5k, indicating that a current pulse was produced at the leader tip and propagated down along the channel. The time gap of the two full brush-like streamer areas (as shown in Figure 5c–5k) was 55.3 μs, which can be regarded as the inter-step interval. The average 2-D velocity of the leader progression was about 0.7×10^5 m/s, while the 2-D transient speed during the stepping moment was larger than 5.7×10^5 m/s (Wang ZC et al., 2016).

It has been suggested that the positive streamers in front of a positive leader propagate in the direction of the electric field and carry electric currents in the propagation direction, while the negative streamers ahead of a negative leader develop in the opposite direction (Williams, 2006; refer also to Figure 6). Here it is worth noting that the positive leader seems to share similar characteristics with stepped negative leaders, as is evident from the streamer area ahead of the leader tip in both cases. The streamer is usually considered to be a cold discharge that changes faster with much fainter brightness than the lightning channel, and that it is too difficult to observe its detailed structure and development process in lightning. Based on our high-resolution observation, it is obvious that the streamer zone at the positive leader tip is crucial to leader propagation. As for the stepping process of the UPL step, there is no 'space stem' observed ahead of the UPL, but we do observe bright corona zones ahead of the leader.

The phenomenon of bright and structured corona streamer bursts during stepping processes was also captured in laboratory sparks for classical negative stepping leaders and "restrike" positive leaders by Kostinskiy et al. (2018). They found that the streamer bursts exhibited nearly spherical symmetry and were essentially independent of the polarity. The newly developed channel segments were nearly straight, with lengths from about 50 cm to over 120 cm, while most steps of the negative leader featured 2-D lengths of some tens of centimeters. Under higher absolute humidity or longer voltage rise times, larger steps could occur for the positive leader. These observations confirm that both stepped and continuously propagation is possible for positive lightning leaders, although the stepped manner is different from that of negative leaders.

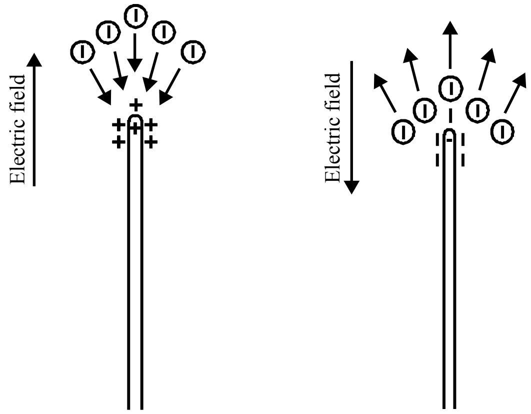

Figure 6. The schematic diagram showing the direction of electron movement associated with positive and negative leader tips.

Comparisons between parameters associated with the UNLs and the UPLs, from rocket-triggered and tower-initiated lightning, are summarized in Table 1. The charge transferred during one step is 383.2 μC for the UNLs, nearly an order larger than that of the UPLs. Besides, the average transient 2-D speed of a positive leader for the tower-initiated lightning is estimated to be 7.3×10^5 m/s, almost an order larger than that of its average 2-D speed (Wang ZC et al., 2016).

5. Positive Recoil Leader in Upward Lightning

The recoil leader was first proposed based on the electric field changes of lightning discharges, named as "K-changes". Then Ogawa and Brook (1964) suggested that K-changes should be negative "recoil streamers" which occur when the positive leader propagates within the cloud and reaches a region of concen-

Table 1. Parameters associated with upward negative leaders (UNLs) and upward positive leaders (UPLs)

	GM of UNLs in 2 triggered flashes (Pu et al., 2017)	GM of UPLs in 4 triggered flashes (Jiang et al., 2013)	GM of UPLs in a tower flash (Wang et al., 2016b)	AM of UPLs triggered flashes (Biagi et al., 2011)
Current pulse interval (μs)	23.0	19.9	60.1	21.2
Half peak width (μs)	2.1	1.0	–	–
$t_{10\%–90\%}$ (μs)	1.3	0.5	–	–
Peak current (A)	90.4	45	–	59
Charge of current pulse (μC)	383.2	54.8	–	64
Step length (m)	6.3 (4.9–8)	(1–4)	4.5	(0.4–2.2)
Charge per unit meter of one step (μC/m)	73.5 (53.6–93.4)	–	–	51
Avereage 2-D speed (10^5 m/s)	2.1 (0–4.46)	1.0 (0.2–1.8)	0.7	(0.6–2.1)

trated negative charge. Mazur (2002) used recoil leader instead of recoil streamer because the developing leader process is constituted of a hot plasma discharge channel with a limited zone of cold streamer filaments in front of the tip of the channel. Recently, based on high speed video camera observations, the recoil leaders have been found to develop in bidirectional fashion with bipolar leaders, and the negative ends propagate along previously existing cooled or decayed positive leaders (Mazur, 2002; Mazur et al., 2013).

Different from previous observations of recoil leaders with negative leader retrograding into the preexisting positive channel, we observed positive recoil leaders with positive leader retrograding in a preexisting negative channel. Figure 7 shows the discharge channels which initiated with a UPL from a high structure. Three obvious channel branches can be observed, with branches *a* and *b* associating with recoil leader events, respectively.

The first recoil leader occurred in branch *a*. From the video frames in the middle panel in Figure 7, it can be seen that a negative leader progressed downward with weak luminosity (Frame −2 to 0) and stopped at Frame 0. At Frame 1, bidirectional leaders developed and propagated in opposite directions. The 2-D partial speed was about 1.2×10^6 m/s. At Frame 5, a new bright segment (channel *b*) appeared and connected to the main leader channel *a*. The newly formed branch *b* retained high luminosity and progressed to the ground, while channel *a* dimmed and soon died out. The new downward leader from branch *a* propagated quickly and reached the former downward leader tip, resulting in an enhanced speed (from 1.4×10^6 m/s to 4.1×10^6 m/s).

The second recoil leader occurred 55.6 ms after the first one. Figure 8 shows the whole process together with leader speeds in different stages. Similar to the first recoil leader, at first, a negative leader progressed downward (Frame −6 to −4), with 2-D speed of 9.0×10^6 m/s. As the leader progressed, its speed decreased from 1.1×10^7 to 1.6×10^6 m/s (Frames −4 to −1). It stopped at about 2.2 km above ground with dramatically reduced channel luminosity. At Frame 0, a bidirectional leader ignited. Based on electric field changes measured 980 m distant, we infer that the upward end was positive while the downward was negative. The downward negative leader induced a negative return stroke (not shown here).

From Figure 8, the speed of the positive end was faster than that of the negative end. The 2-D partial speed of the upward end was from 3.2×10^6 m/s to 1.1×10^7 m/s with an average value of 6.4×10^6 m/s. while the downward end propagated at $1.0–3.2\times10^6$ m/s with an average value of 2.2×10^6 m/s, almost one third of the upward one. The speed of the two ends increased with time. It is in-

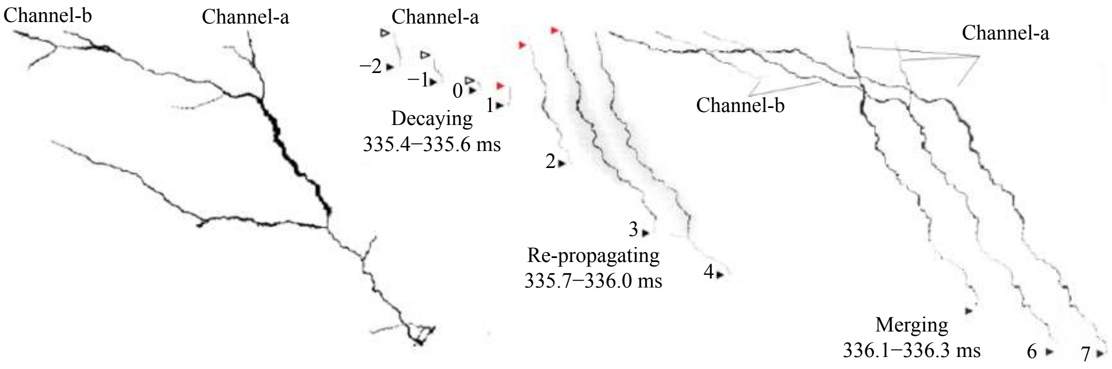

Figure 7. The lightning discharge channels which initiated with an upward positive leader from a high structure. Left: whole discharge channel. Middle and right: first recoil leader processes. Note that the image color is inverted for better presentation. Numbers denote the frame number with 0 representing the start of the bidirectional leader.

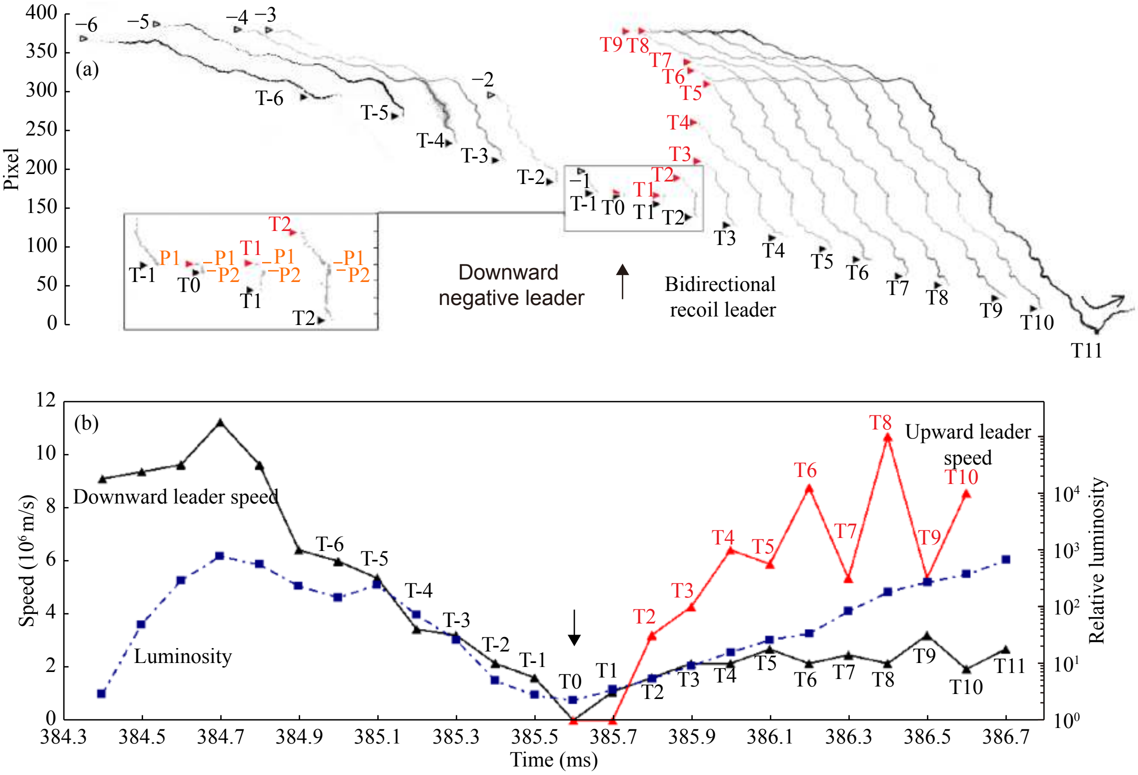

Figure 8. Consecutive color-inverted frame images revealing the recoil leader development (upper panel) and the corresponding 2-D partial speeds (lower panel). The numbers correspond to the frame number and time instant. The time variation of average relative luminosity of the channel is also shown in the figure (Adapted from Jiang RB et al. (2017)).

teresting to note that the velocity of the upward end is inversely correlated to the speed of the downward end. From Frame T4 to Frame T10, the increasing speed of the upward end correlated to decreasing downward propagation, indicating that the two ends may interact through a kind of inhibition between each other (Jiang RB et al., 2014).

Similar recoil leaders were captured in two rocket-triggered lightning discharges. Based on high speed camera observations, Qie XS et al. (2017) found that a negative downward leader stopped midway before reaching the ground, and the bi-leader developed almost immediately below the decayed leader tip. The upward leader end was positive and retrogressed along the existing negative channel with an average speed of about 2×10^6 m/s, roughly two times faster than the negative downward leader end. It is notable that in all these cases, the polarity of the recoil leader was completely reversed to the traditional one (Mazur, 2002; Mazur et al., 2013; Warner, 2012; Mazur and Ruhnke, 2011).

6. Conclusion and Discussion

The stepping and branching manners of the UNL in the very initial stage of positive rocket-triggered lightning flashes have been presented and confirmed by simultaneous comprehensive optical and electromagnetic detection datasets. The stepwise propagation of a negative leader involves 5 stages: (i) streamer zone formation at the leader tip, (ii) the main leader channel dim, and stem emergence in front of the leader tip, (iii) positive streamer propagating retrogradely from the stem and negative streamer forward, (iv) the backward positive streamer well connecting to the main leader tip, and (v) channel illuminating and leader stepping forward. One or more space stems may appear ahead of the leader tip, and they propagated bidirectionally with the positive end connecting retrogradely to the main leader tip and the negative end propagating forward to form the leader channel branching. If the stem is not right in the leader forward direction, the leader channel will be winding. The essential stems ahead of the leader tip not only determine the manner of leader propagation, but also the propagation direction, and the branching and winding accordingly. The speed of the main UNL was evidently related to the branching during the initial stage. However, the non-branching UPL in negative-triggered lightning also presents intermittent stepwise propagation. UNL transferred charge of 383.2 μC in a step, which is almost one order of magnitude larger than that of the UPL.

Tower-initiated lightning supports the step-like propagation pattern of UPL. Nevertheless, the stepwise propagation is different from the manner of negative leaders. A positive leader step is divided into 3 stages: (i) charge accumulation at the channel tip and streamer appearance , (ii) positive streamers burst from the leader tip, and current flow back from the leader tip, and (iii) channel illuminating and leader stepping forward, which appears as periodic emergence of faint brush-like corona zones near the leader tip and the periodic re-illumination of the channel body. It is important to note that a negative streamer zone exists ahead of the negative leader tip, while a positive streamer zone exists ahead of the positive leader tip. However, due to visibility limits, the streamer zone may usually be too faint to be captured by the camera for both polarities. One or more streamer segments may become the space leader or stem igniting the branching behavior of a negative leader.

Although the positive leader channel can progress in a stepping fashion, it is different from the negative leader stepping. The different structure between positive and negative streamer zones ahead of the leader tips may cause disparate stepping processes. The electron drift motion is divergent resulting in the streamers easily become weak for negative breakdown , while that is convergent for positive breakdown leading to a more favorable condition for the positive breakdown to initiate and propagate. This is the mechanism to explain why positive leaders propagate continuously and negative leaders are stepped in laboratory long air-gap discharges (Williams, 2006). The different structure and composition of the streamer system ahead of the lightning leader in two polarities here confirm this idea.

The positive streamers are essential in the leader stepping processes for both polarities. In the negative leader scenario, it seems that the positive streamers from the stem play a crucial role to fulfill the individual step and they travel backward from the stem to the leader tip, while in the positive leader scenario, the positive streamers traverse forward from the leader tip.

High-resolution observation of tower lightning also revealed a polarity-inverted recoil leader with contrary to the traditional one. The formation of recoil-leaders should be related to instability of the lightning channel due to its low conductivity.

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