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Key Points:

- Leaders exhibit branching inside the common streamer zone
- Positive and negative leaders have similar speeds in the common streamer zone
- Downward leader can connect to upward leader below its tip

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Observations of the connection of positive and negative leaders in meter-scale electric discharges generated by clouds of negatively charged water droplets

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Abstract Detailed observations of the connection between positive and negative leaders in meter-scale electric discharges generated by clouds of negatively charged water droplets are presented, and their possible implications for the attachment process in lightning are discussed. Optical images obtained with three different high-speed cameras (visible range with image enhancement, visible-range regular, and infrared) and corresponding current recordings were used. Two snapshots of the breakthrough phase of the leader connection, showing significant leader branching inside the common streamer zone, are presented for the first time. Positive and negative leader speeds inside the common streamer zone for two events were found to be similar. Higher leader speeds were generally associated with higher leader currents. In the case of head-to-head leader connection, the infrared brightness of the junction region (probably representing the gas temperature and, hence, the energy input) was typically a factor of 5 or so higher than for channel sections either below or above that region. In 16% of cases, the downward negative leader connected to the upward positive leader below its tip (attached to the lateral surface of the positive leader), with the connection being accomplished via a channel segment that appeared to be perpendicular to one or both of the leader channels.

1. Introduction

It is known [e.g., Berger, 1977, p. 178; Golde, 1977, p. 555; Bazelyan and Raizer, 1998, p. 2] that the phenomenology of long laboratory sparks is similar to that of lightning. For this reason, many terms first introduced for lightning (for example, leader and return stroke) have been adopted for sparks and vice versa (for example, midgap or space stem/leader). Some basic lightning mechanisms (for example, formation of negative leader steps) were first discovered in sparks [Gorin et al., 1976] and only recently were observed in lightning [Biagi et al., 2010; Gameraota et al., 2014]. The reason is clear: observations of sparks can be performed at much closer distances and for a much larger number of events. The terms “attachment process” and “breakthrough phase (final jump)” are applied to both lightning (natural phenomenon) and laboratory sparks (artificial phenomenon); further, the same terminology is used for rocket-and-wire-triggered lightning, which, although artificially initiated, is a full-scale lightning discharge whose energy source is the natural thundercloud (see, for example, Rakov and Uman [2003, Ch. 4 and 7] and references therein).

Artificially charged clouds of water droplets generating “electrodeless” electric sparks [e.g., Vereshchagin et al., 1988; Antsupov et al., 1991; Temnikov et al., 2007; Syssoev et al., 2014] have been recently used for studying a variety of discharge processes that are known or expected to occur in lightning but do not easily render themselves to the traditional observational techniques. Specifically, Kostinskiy et al. [2015a], using a high-speed infrared camera, have observed unusual plasma formations in artificial clouds of negatively charged water droplets. Inferred plasma parameters were close to those of leaders observed in the same experiments, while the channel morphology was distinctly different from that of leaders. These formations appear to be manifestations of collective processes building, essentially from scratch, a complex hierarchical network of interacting channels at different stages of development. Kostinskiy et al. [2015a] suggested that the phenomenon should commonly occur in thunderclouds and might give insights on the missing link in the still poorly understood lightning initiation mechanism. Kostinskiy et al. [2015b] have obtained detailed infrared images of

bidirectional leaders produced by the cloud of positively charged water droplets. The leader was composed of a downward extending positive part and an upward extending negative part, these two parts (both branched) being connected by a single-channel middle part. The upward extending part was associated with an extensive network of faintly luminous channels pervading the upper part of the cloud. *Kostinskiy et al.* [2015c] have demonstrated the possibility of initiation of electric discharges by a crossbow bolt (projectile) moving in the electric field of a cloud of negatively charged water droplets.

In this paper, we present detailed observations of the connection between positive and negative leaders in meter-scale electric discharges to ground generated by clouds of negatively charged water droplets and discuss their possible implications for the attachment process in lightning. The lightning attachment process, which can be viewed as the transition from leader to return stroke, is one of the most poorly understood lightning processes, primarily due to its short duration and frequent occurrence in the same frame as the return stroke in high-speed video records. The attachment process in negative strokes is generally assumed to include a positive upward connecting leader (UCL) and the so-called breakthrough phase [*Rakov and Uman*, 2003, chapter 4]. To date, the breakthrough phase (also referred to as the final jump) along with the UCL was observed in long sparks [*Lebedev et al.*, 2007; *Shcherbakov et al.*, 2007] and in rocket-and-wire-triggered lightning [*Biagi et al.*, 2009; *Hill et al.*, 2016], but not in natural lightning.

In either lightning of long sparks, the breakthrough phase starts when the relatively low conductivity streamer zones of positive and negative leaders come in contact (or the streamer zone of positive leader converges on the negative leader tip) to form a common streamer zone. The subsequent extension of the two relatively high conductivity plasma channels toward each other takes place inside the common streamer zone. The common streamer zone can be formed in downward cloud-to-ground lightning (near ground), in upward lightning (aloft), and during the negative leader step-formation process (between the positive end of space leader and the negative leader tip). Once the two plasma channels make contact with each other, the return stroke (also referred to as the main stage) or return-stroke-like process begins. The common streamer zone is thought to be characterized by the average electric field of about 500 kV/m (5 kV/cm), regardless of the type of electric discharge. It is this field, rather than the electric potential or gap length, that largely determines the physical processes inside the common streamer zone. Therefore, we believe that characterization of the breakthrough phase in sparks can be useful for improving our understanding of its counterpart in lightning.

In section 3.1, for sparks produced by the artificial, negatively charged cloud, we present visible-range images of the breakthrough phase in conjunction with corresponding current and light intensity records. Positive and negative leader dynamics inside the common streamer zone are examined. Further, an example of infrared image of the junction region between the colliding head-to-head downward and upward leaders inside the cloud is given in section 3.2. Finally, in section 3.3, we show a scenario in which the descending negative leader (actually the lower, negative part of the bidirectional leader) attaches to the lateral surface of the upward connecting positive leader.

2. Experimental Setup

The experimental setup is shown in Figure 1 of *Kostinskiy et al.* [2015b]. The jet-shaped cloud of negatively charged water droplets was formed above a grounded metal plane. Typical radius of water droplets was about 0.5 μm (ranging from 0.2 to 0.7 μm). The height of the upper boundary of the cloud over the grounded plane was up to 4 m. The observed connections of oppositely charged leaders occurred 10–30 cm below the lower cloud boundary, except for those imaged at infrared inside the cloud.

Electric discharges of the order of 1 m in length spontaneously occurred between the cloud and grounded objects nearby when a sufficient amount of charge accumulated in the cloud. For a negatively charged cloud, a majority of the discharges started with upward positive leaders from an instrumented grounded metallic sphere of 5 cm diameter located 12 cm above the plane and 0.8–0.9 m from the plane center. This allowed us to measure the discharge current with a 1 Ω resistive shunt, connected to a digitizing oscilloscope.

Optical observations were performed using two high-speed framing cameras operating in the visible range (4Picos and FASTCAM SA4) and an infrared (2.7 to 5.5 μm) high-speed framing camera FLIR SC7700M. The infrared camera had a resolution of 640 \times 512 pixels and operated at 111 frames per second with frame duration of 9 ms and exposure time of 8.7 ms. The FASTCAM SA4 camera was operated in the pretriggered mode at

50,000 frames per second, with resolution of 320×192 pixels. Two frames separated by 500 ns or more, with 1360×1024 pixels each, were produced by the 4Picos camera. 4Picos had a built-in image intensifier whose optical gain was 5×10^3 . The exposure time of 4Picos frames could be set in the range from 0.2 ns to 80 s. The spatial resolution (pixel size) was 0.63 mm for 4Picos, 1.2 mm for FLIR, and 1.46 mm for FASTCAM. The cameras were triggered when current through the 5 cm sphere exceeded a preset threshold value.

Additionally, variation of light intensity was recorded using a photomultiplier operating in the visible range and pointing in the same direction as the high-speed cameras. Overall pictures of discharges were obtained using a digital still camera (Canon EOS 5D Mark III). Cameras were installed at a distance of about 3 m from the cloud.

A more detailed description of the overall experimental setup can be found in *Kostinskiy et al.* [2015b].

The experiments were conducted in May of 2014 at the outdoor high-voltage research facility located in Istra, Moscow region, Russia. The temperature was 10 to 15°C, and the relative humidity was 90–95%. The cloud was charged to 50–100 μC , and the electric field on the grounded plane 0.8 m from the cloud axis, measured with a field mill, was 400–500 kV/m.

All the discharges considered in this paper exhibited connection between the descending negative leader (which is the lower part of bidirectional leader initiated in the cloud) and the upward positive leader initiated from the grounded plane. In this regard, they are similar to downward negative lightning strokes. In both cases, the connection results in bright illumination of the entire channel and a fast-rising current pulse measured at ground, which are considered to be manifestations of the return-stroke process in the case of lightning. We will apply the term return-stroke-like process to the similar process in the discharges generated by artificially charged clouds. Note that current peaks for the latter are typically 10 to 100 A and current pulse durations are of the order of a microsecond versus tens of kiloamperes and hundreds of microseconds, respectively, for lightning. Further, typical charge transfer by a negative lightning first stroke is about 5 C, while the total charge of the artificially charged cloud in these experiments was less than 100 μC (less than the charge of a single lightning leader step). Additionally, in contrast with downward negative lightning, it is possible that in our discharges the upward positive leader was initiated before the onset of downward negative leader in the cloud. It is important to note that the significant differences in terms of the charge transfer and return-stroke current waveform listed above are not likely to materially influence (at least qualitatively) the processes in the common streamer zone, which are the focus of this paper. Indeed, the discharge processes in the streamer zone of a leader are determined by the electric field produced by the charges of leader tip, charges on a short segment of leader channel (including its corona sheath) just behind the tip, and charges of streamers forming the streamer zone; they only weakly depend on the large-scale external electric field produced by charges in the cloud, on leader branches (if any), etc. During the breakthrough phase, the electric field intensity inside the common streamer zone increases and the influence of the external field on the processes there becomes even less significant.

3. Observations

3.1. Breakthrough Phase Recorded With the Image-Enhancement Camera

Two pairs of 4Picos frames with corresponding current and light intensity records will be presented here. The timing uncertainty was 20–40 ns.

The first pair is shown in Figure 1. The exposure time for each frame was 100 ns, and the time interval between frames was 2 μs . In frame (I), the streamer zones of the downward negative leader 1 and the upward positive leader (UPL) 2 are in contact, forming the common streamer zone 3, so that the breakthrough phase is in progress. Note that the UPL, whose total length (estimated in frame II) is about 1 m, is branched, while the descending negative leader is not. The length of the common streamer zone is about 17 cm. It is thought that streamers mostly radiate at UV (300–400 nm). The 4Picos wavelength range (315–850 nm) covered a significant portion of the UV range. In frame (II), the later stage of the return-stroke-like process is seen. Note that the relatively low luminosity spots in frame (II) at the positions of bright leader tips in frame (I) are camera artifacts. The reason for the artifact is that the time between frames is insufficient for the full recovery of luminophore used in the camera's image intensifier. The corresponding records of current and light intensity, as well as the camera trigger signal and exposure times of the two frames (see Figure 1), are shown, on two different time scales, in Figures 2a and 2b. The current and light intensity records exhibit

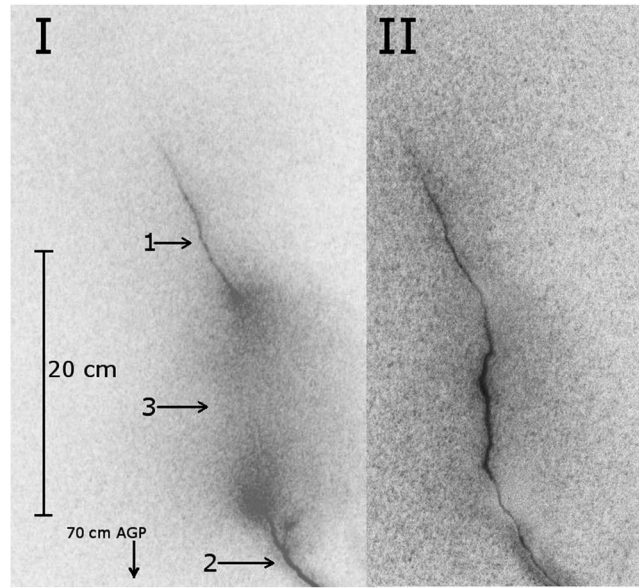


Figure 1. Two 4Picos frames showing the breakthrough phase (I) and later stage of return-stroke-like process (II) of a negative discharge to ground generated by the cloud of artificially charged water droplets. The exposure time for each frame is 100 ns, and the time interval between frames is 2 μ s (see trace 4 in Figure 2). Labeled are the downward negative leader 1, upward positive leader 2, and the common streamer zone 3. Image (II) was considerably fainter than image (I) (due to a considerably lower current corresponding to image (II); see traces 1 and 4 in Figure 2b) and was contrast enhanced more than image (I), to improve its visualization. AGP stands for “above the grounded plane.”

two peaks, the first, smaller one corresponding to the breakthrough phase and the second, larger one to the return-stroke-like process (at least for the light intensity pulses; current pulses are clipped at 8 A). The time interval between the two peaks is about 1.4 μ s. The breakthrough-phase current decreases after its peak exceeding 8 A and is 4.9 A (in the minimum of oscillation cycle) immediately prior to the return-stroke-like process onset. (Here and in the following, all currents are absolute values and the return-stroke onset is identified by the sharp increase of current.) The current decay after its first (breakthrough phase) peak exhibits oscillations with peak-to peak amplitudes ranging from 0.6 to 1.9 A. On average, the current decreases from 7.8 A at the end of the first frame to 5.7 A at the return-stroke-like process onset.

Seen in Figure 3 are two 4Picos frames showing two snapshots of the breakthrough phase of a negative discharge to ground generated by the cloud of artificially charged water droplets. To date, this is the only two-frame

image of the breakthrough phase of the connection of oppositely charged leaders. The exposure time for frame (I) was 100 ns, and for frame (II) it was 50 ns. The time interval between frames was 2 μ s. Labeled are the downward negative leader 1, upward positive leader 2, and the common streamer zone 3. The length

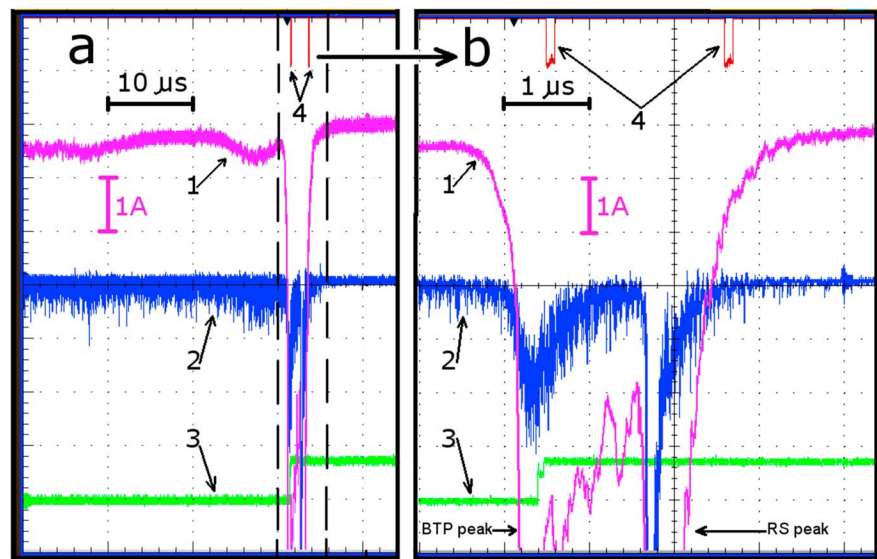


Figure 2. Records of current 1 and light intensity 2 corresponding to the two 4Picos frames shown in Figure 1. Also shown are the camera trigger signal 3 and exposure times of the two frames 4. All records are shown on two time scales: (a) 10 μ s per division and (b) 1 μ s per division. Vertical broken lines in Figure 2a indicate the overall time interval shown in Figure 2b. BTP and RS stand for the “breakthrough phase” and “return-stroke-like process,” respectively.

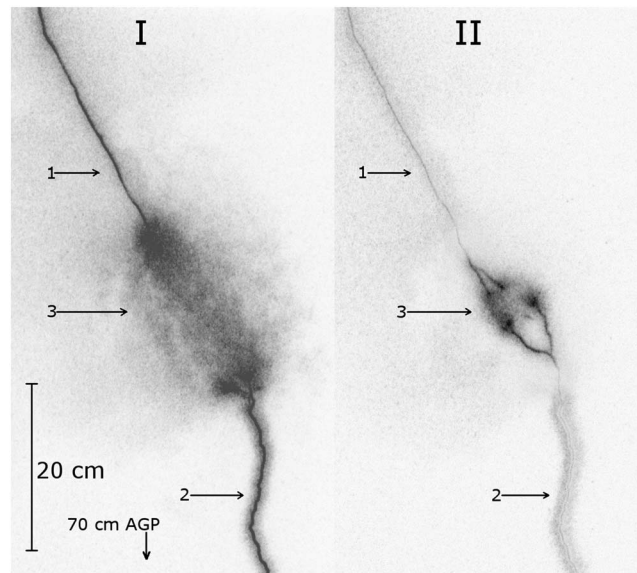


Figure 3. Two 4Picos frames both showing the breakthrough phase of a negative discharge to ground generated by the cloud of artificially charged water droplets. The exposure time for frame (I) is 100 ns and for frame (II) it is 50 ns. The time interval between frames is 2 μ s. Labeled are the downward negative leader 1, upward positive leader 2, and the common streamer zone 3. AGP stands for above the grounded plane.

of the common streamer zone (the distance between the leader tips) is about 20 cm in frame (I) and is about 4.5 cm in frame (II). Note that only the upward positive leader in (I) is branched, while in (II) both upward positive and downward negative leaders exhibit pronounced branching. (The extension speeds of individual branches are examined in section 4.) In fact, there are two common streamer zones in frame (II) (the single common streamer zone seen in frame I is transformed into two common streamer zones in frame II) and it is likely that two junction points were formed leading to a loop or split in the channel of return-stroke-like process (although no image of the latter is available for this event), a feature that is occasionally seen in both laboratory sparks and lightning. The corresponding records of current and light intensity, as well as the camera trigger signal and exposure times of the two frames (see Figure 3), are

shown, on two different time scales, in Figures 4a and 4b. Similar to Figure 2, the current and light intensity records exhibit two peaks, the first one corresponding to the breakthrough phase and the second one to the return-stroke-like process. However, in this case the light-intensity peak of the return-stroke-like process is smaller than that of the breakthrough phase. The time interval between the two peaks is about 2.4 μ s. The breakthrough and return-stroke-like process current pulses are both clipped at 8 A. The breakthrough-phase current during the first frame and during 0.3 μ s after that frame exceeds 8 A. Then it shows a decrease with oscillations, similar to, but less pronounced than those in Figure 2b, and 0.15 μ s prior to the beginning of the second frame reaches a minimum of 3.2 A. During the second frame, the current is at 3.4 A level and then gradually increases to 4 A by the time of the return-stroke-like process onset.

3.2. Brightness of Junction Region Relative to the Higher and Lower Channel Sections (Head-to-Head Connection)

Presented in Figure 5 (left) is an example of infrared (IR) image (one of several hundreds) showing the junction region (completely inside the cloud) between the downward negative and upward positive leaders and brightness profiles (Figure 5, right) corresponding to the upward positive leader 1, downward negative leader 2, and the junction region 3. The positive and negative leaders were identified based on the different degree of tortuosity of their channels: positive leader channels in our experiments were always more tortuous than negative ones. (This is based on our analysis of several hundreds of images for which we knew the upward leader polarity from its measured current. In 100% of cases the positive leader channel was clearly more tortuous than the negative one.) In lightning, the tortuosity of negative leader is apparently associated with its stepping, the process that did not occur in our meter-scale sparks. This is the most likely explanation of the low tortuosity of negative leaders observed in our experiments. Note that the IR brightness of the junction region (probably representing the gas temperature; see Kostinskiy *et al.* [2015a]) is a factor of 5 higher than that corresponding to either positive or negative leader. Note that the image in Figure 5 actually includes the return-stroke-like stage (exposure time was 8.7 ms).

3.3. Connection of Downward Negative Leader to the Lateral Surface of Upward Positive Leader

Figure 6 shows two consecutive frames of the FASTCAM SA4 camera operating at 50,000 frames per second with resolution of 320 \times 192 pixels. The exposure time was 20 μ s with essentially zero dead time. Only the

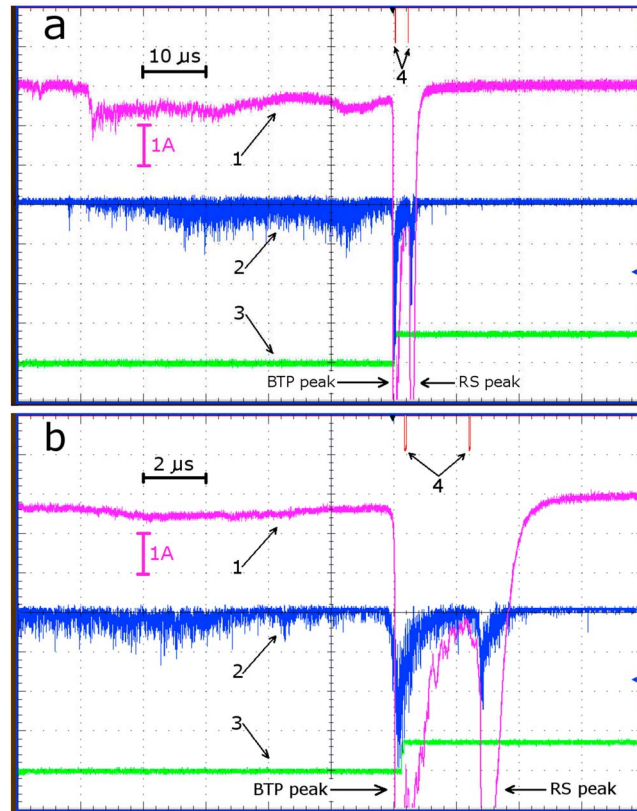


Figure 4. Records of current 1 and light intensity 2 corresponding to the two 4Picos frames shown in Figure 3. Also shown are the camera trigger signal 3 and exposure times of the two frames 4. All records are shown on two time scales: (a) 10 μ s per division and (b) 2 μ s per division. BTP and RS stand for the breakthrough phase and return-stroke-like process, respectively.

upward positive leader from the instrumented sphere is seen in frame 1. In frame 2, the upward positive leader is a little longer and brighter and it is in contact with the descending, negative leader. The positive and negative leaders were differentiated based on the relative level of their tortuosity, as discussed in section 3.2 above. Actually, besides the leaders, the image in frame 2 includes the return-stroke-like process.

The corresponding current record is shown in Figure 7. The initial current peak corresponds to an upward positive streamer corona burst (peak current about 3.8 A, half-peak width 50–100 ns), followed by an upward positive leader developing for about 37 μ s with current decreasing to about 0.2–0.4 A. The sharp current pulse, corresponding to the return-stroke-like process, has a peak of greater than 9 A, a risetime of 80–100 ns, and a half-peak width of about 400 ns, with the overall duration being 1.5–1.7 μ s. As noted above, frame 1 in Figure 6 corresponds to the upward positive leader stage, when the current was relatively low, and frame 2 includes the return-stroke-like process.

Note that the negative leader in Figure 6 connected to the positive leader below

its tip (attached to the lateral surface of the positive leader) and that the connection is accomplished via a channel segment of 4.1 cm in length that appears to be more or less perpendicular to both positive and negative leader channels. We observed such geometry many times in still photographs of negative discharges to ground generated by artificially charged clouds. An example of such photograph is shown in Figure 8.

4. Analysis and Discussion

As noted in section 1, the lightning attachment process, particularly its breakthrough phase (final jump), is one of the most poorly understood lightning processes. There is a very limited number of published optical images of common streamer zone for either lightning or laboratory sparks, and no two-frame images exist in the literature to date. In this regard, the two snapshots captured during the breakthrough phase and shown in Figure 3 provide new insights into the behavior of leaders developing inside the common streamer zone. The breakthrough phase started when the relatively low conductivity streamer zones of upward and downward leaders came in contact to form a common streamer zone. We speculate that the subsequent extension of the two relatively high conductivity plasma channels toward each other inside the common streamer zone can result in either a single connection (see Figures 1 and 5) or multiple connections (resulting in a split channel, as seen in Figure 4.28 of Rakov and Uman [2003] for natural lightning, in Figure 15 of Howard *et al.* [2010] for rocket-and-wire-triggered lightning, and in Figure 3b of Shcherbakov *et al.* [2007] for long laboratory sparks). In the case of multiple connections, there are two possible scenarios: (1) the multiple connections are formed sequentially (probably because the impedance of a single connection is too high) and (2) the multiple connections result from both positive and negative leader channels being forked. This latter scenario seems to be evident in Figure 3, although no image of the resultant return-stroke-like process is available.

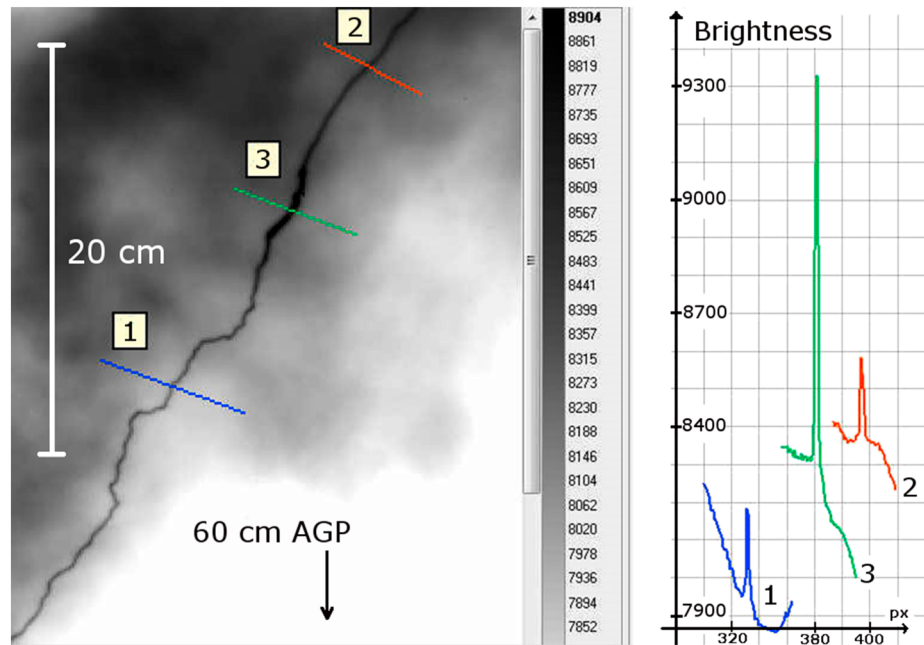


Figure 5. (left) Infrared image showing the junction region (completely inside the cloud) between the downward negative and upward positive leaders (head-to-head connection) and (right) approximate brightness profiles corresponding to the upward positive leader 1, downward negative leader 2, and the junction region 3. In Figure 5 (right), the horizontal axis is the distance (in pixels) along the slanted lines labeled 1, 2, and 3 in Figure 5 (left), and the vertical axis is the brightness in relative units. AGP stands for above the grounded plane.

The two-frame record of the breakthrough phase shown in Figure 3 allowed us to estimate, for the first time, two-dimensional (following the luminous path) propagation speeds of positive and negative leader branches inside the common streamer zone. These speeds turned out to be similar for all four branches (regardless of their polarity) seen in Figure 3 and are between 5.2 and 5.5×10^4 m/s. We additionally estimated the speeds between the second frame and the return-stroke-like process onset (with the distance which was traveled by each of the two oppositely charged branches being found by assuming that those branches propagated at the same speed and came in contact when the return-stroke-like process began, at the time identified in

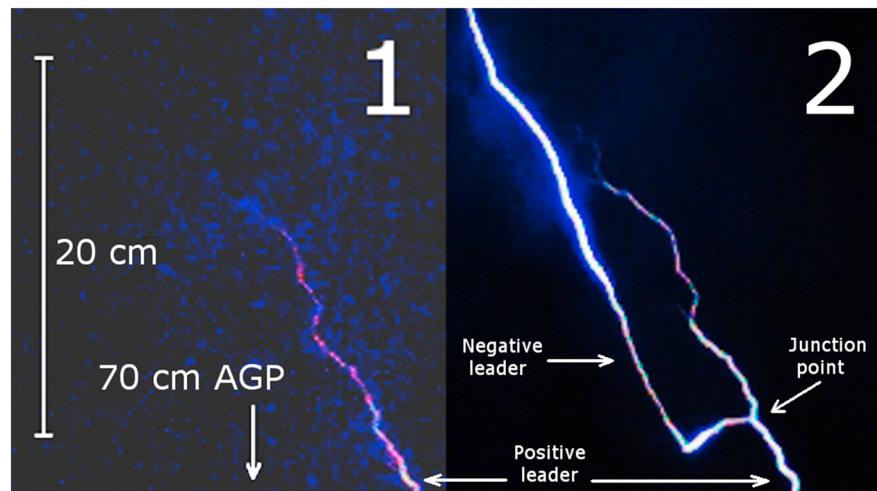


Figure 6. Two consecutive $20 \mu\text{s}$ frames of FASTCAM SA4 camera showing connection of the downward negative leader to the upward positive leader below its tip. About 16% of our discharges exhibit this behavior. The positive and negative leaders were identified based on the current record and the experimentally determined dependence of leader channel tortuosity on polarity (for several hundreds of cases examined, the positive leader channel was always noticeably more tortuous than the negative one). AGP stands for above the grounded plane.

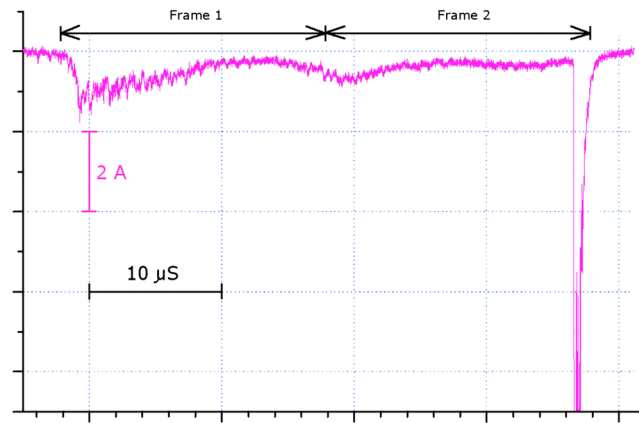


Figure 7. Current record corresponding to the two FASTCAM SA4 frames shown in Figure 6.

between the first frame of the breakthrough phase shown in Figure 1 and the return-stroke-like process onset (see Figure 2b) are 8.5×10^4 m/s.

According to *Andreev et al.* [2008], the propagation speed v_L (in cm/ μ s) of positive leader in sparks, regardless of the stage of its development (including the breakthrough phase), is related to leader current i_L (in A) by the following equation: $v_L = 1.88 \times i_L^{0.67}$. Our measured leader speeds and corresponding speeds calculated using measured currents and the empirical formula of Andreev et al. are summarized in Table 1 (assuming that the currents in positive and negative leaders in the same event are equal to each other). The measured speed values are somewhat higher than their counterparts predicted by Andreev et al.'s equation (see also Figures 6 and 9 of *Popov* [2009]), but the general trend for increasing speed with increasing current is confirmed by our data. Note that for the event shown in Figures 3 and 4, the current in individual branches should be lower than (probably about one-half of) the current measured at the grounded plane, so that the corresponding calculated speeds given in Table 1 should be lower. For comparison, the average current of negative lightning stepped leaders is of the order of 100 A. The corresponding leader speed, according to Andreev et al.'s formula derived for positive leaders in sparks, is 4.1×10^5 m/s, which is similar to the measurements (4.0×10^5 and 5.5×10^5 m/s) for 100 A leader currents in sparks cited by *Popov* [2009] and not far from typical values measured for negative stepped leaders in lightning.

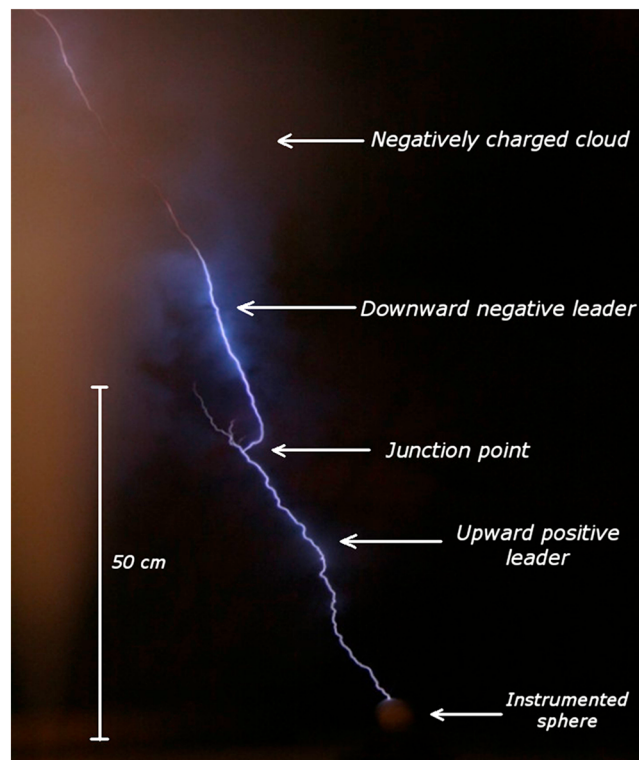


Figure 8. Still picture showing a downward negative leader making contact with an upward positive leader below its tip. Leader polarity was identified based on the current record and the experimentally determined dependence of leader channel tortuosity on polarity (for several hundreds of cases examined, the positive leader channel was always noticeably more tortuous than the negative one). Exposure time was 2 s.

the current record shown in Figure 4b). The resultant speeds are 5.1 and 5.5×10^4 m/s, very similar to the speeds between the first and second frames. This result is somewhat surprising because it is expected that the positive and negative leaders accelerate toward each other inside the common streamer zone. It may be related to the fact that the currents in the two time intervals used for measuring speed were about the same. Similarly (assuming that positive and negative leader branches propagated at the same speed and came in contact when the return-stroke-like process began) estimated leader speeds

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In both Figures 2b and 4b, the current exhibits two pronounced peaks, the first one corresponding to the breakthrough phase and the second one to the return-stroke-like process. The time intervals between the two peaks (exceeding 8 A)

Table 1. Comparison of Measured Leader Speeds in the Common Streamer Zone With Those Estimated From Measured Currents and the Empirical Formula of *Andreev et al.* [2008]

Reference	Measured Current Range (A)	Measured Speed (m/s)	Calculated Speed Range (m/s)
Figures 1 and 2, fframe 1 to RS onset	5.7 to 7.8 (decreasing)	8.5×10^4	6.0×10^4 to 7.4×10^4
Figures 3 and 4, frame 1 to frame 2	3.2 to >8 (mostly decreasing)	5.2×10^4 to 5.5×10^4	4.1×10^4 to $>7.6 \times 10^4$
Figures 3 and 4, Frame 2 to RS onset	3.4 to 4 (increasing)	5.1×10^4 to 5.5×10^4	4.3×10^4 to 4.8×10^4

are about 1.4 and 2.4 μs in Figures 2b and 4b, respectively. The corresponding currents immediately prior to the return-stroke-like process onset are about 5.7 and 4 A. It is not clear why the breakthrough-phase current significantly decreases after its peak. Perhaps, the streamer connection fails to lead to direct transformation of the common streamer zone to a hot channel that would facilitate the tapping of the cloud charge in a single pulse. We speculate that such transformation is a complex process that involves competition between the creation and decay of multiple links and possibly floating channel segments in the connection region between the leader tips. This competition is possibly influenced by the streamer space charge serving to reduce the electric field near the hot leader channel from which the streamers originate and thereby limit the current. The observed phenomenon possibly suggests that a sequence of breakdowns may be involved in bridging the common streamer zone. Indeed, if, after the initial connection, the impedance of the connection region and the resultant voltage drop remain sufficiently high, an additional breakdown across that region may create an additional connection, in parallel with the initial one. In lightning, there is some evidence that the breakthrough phase is not a single jump, as the synonymously used term “final jump” suggests. It apparently involves multiple connections, as evidenced by multiple-station dE/dt measurements for natural and rocket-and-wire-triggered lightning reported by *Howard et al.* [2010]. They examined the so-called fast-transition (FT) pulse, as well as multiple pulses occurring during the preceding slow front (SF) whose duration for first strokes is typically some microseconds and whose onset signifies the beginning of the breakthrough phase of the lightning attachment process. The FT pulse and the SF pulses were all inferred to be of the same nature and associated with multiple connections sequentially made between downward negative and upward positive leaders during the breakthrough phase. *Howard et al.* presented in their Figure 15 an optical image (video frame) showing a split triggered-lightning channel with two primary connections, one of which showing a smaller split (two subconnections), so that the total number of imaged connections was three. They related these three connections to the three major SF/FT pulses seen in their dE/dt records (see their Figure 14), which suggests that those connections were established at different times (sequentially) over the 2.1 μs duration of the breakthrough phase. Our event shown in Figure 3 may be of the kind described by *Howard et al.* [2010], although we do not have the image of return-stroke-like process to state this without reservation. Interestingly, the triggered-lightning event studied by *Howard et al.* [2010] exhibited a 20 kA abrupt increase in the channel-base current associated with a SF pulse. Another sharp current rise occurred later, at the time of the FT pulse. The overall current peak was 45 kA (unusually high). More recently, *Hill et al.* [2016] related each of the SF/FT pulses in triggered-lightning strokes they studied with a fast, kiloampere-scale increase in the channel-base current followed by a decrease in current rate of rise (although not by a decrease in the current, as in our events shown in Figures 1–4). The arithmetic mean duration of the breakthrough phase in their study was 1.77 μs , and the mean current just prior to the initiation of the breakthrough phase was 16.7 A. The onset of breakthrough phase was associated with an increase in the channel-base current to typically many hundreds of amperes.

In lightning, once the plasma channels of the downward and upward connecting leaders make contact with each other inside the common streamer zone, the return-stroke stage begins. It starts with two return-stroke current waves initiated from the junction point of the two leaders. One current wave moves upward, toward the cloud, and the other moves downward, toward ground [*Wang et al.*, 1999, 2013, 2014a; *Jerauld et al.*, 2007]. The downward wave is expected to be short lived and, after its reflection from ground, probably catches up with the upward wave front [e.g., *Rakov*, 2013]. A single upward moving return-stroke wave is eventually formed. There may be also current waves associated with multiple connections during the breakthrough phase discussed above. *Hill et al.* [2016] inferred from their correlated dE/dt and dI/dt records that each SF/FT pulse was associated with a current wave propagating from the junction point (connection region) to ground. They estimated that for SF pulses the speeds of those waves were 4.3×10^7 to 1.6×10^8 m/s, and for FT pulses they were 1.2×10^8 to 1.6×10^8 m/s.

Our observations of head-to-head connections show that, in the infrared range, the section of plasma channel that replaces the common streamer zone is significantly brighter than the channel sections above and below it (see Figure 5). *Kostinskiy et al.* [2015a], based on their analysis, concluded that the brightness of the infrared images obtained with our FLIR camera can be viewed as representing the final gas temperature of the imaged plasma channel. This means that the channel in the neighborhood of the junction point is hotter or/and thicker than the channel sections either above or below the junction region. It appears that the largest energy input into the lightning channel near ground is associated with the breakthrough phase, during which the oppositely charged leader channels are expected to be accelerated to their collision. Interestingly, the enhanced brightness near the junction point has never been reported from time-integrated, visible-range images of lightning, although *Wang et al.* [2014b] found that the peaks of light pulses are the highest near the junction point.

Lu et al. [2013], using high-speed photography, reported on the lightning attachment process involving connection of downward negative leader to the lateral surface of the oppositely charged upward connecting leader (UCL). The UCL was about 400 m in length and developed from the building of comparable height. It was as bright as or brighter than the descending negative leader. They interpreted the phenomenon (connection below the tip) as UCL being guided by the overall electric field of multiple branches of the descending leader, rather than being primarily attracted by the single branch that eventually makes connection. The connections between the downward negative leader and upward positive leader shown in our Figures 6 and 8 are remarkably similar to that observed in downward natural lightning by *Lu et al.* [2013]. In a follow-up study, *Lu et al.* [2016] reported on the two basic types of connection between downward negative and upward positive leaders in natural lightning: the tip-to-tip (head-to-head) connection and the connection of negative leader to the lateral surface of positive leader. Out of their 24 events observed with high-speed video cameras, 10 (42%) exhibited the first type of connection, 12 (50%) the second type, and 2 (8%) a combination of the first and second types. They never observed connection of an upward positive leader to the lateral surface of downward negative leader. In order to compare the occurrence of different types of leader connection in our meter-scale sparks with *Lu et al.*'s [2016] results for downward lightning, we examined an additional data set acquired on 13 May 2016. A total of 268 discharges exhibiting connection of the downward negative and upward positive leaders were observed. Out of these 268, in 78.7% of cases the leaders contacted head-to-head and in 15.7% of cases the negative leader attached to the positive leader below its tip. Additionally, in 5.6% of cases the leaders developed parallel to each other and failed to form a common plasma channel (communicated only via their streamer zones). Similar to *Lu et al.*'s observations, we have never seen the connection of upward positive leader to the lateral surface of downward negative leader.

5. Summary

1. High-speed video camera observations along with synchronized current records of the connection between positive and negative leaders in meter-scale electric discharges generated by clouds of negatively charged water droplets are presented, and their possible implications for the attachment process in lightning are discussed.
2. Two snapshots of the breakthrough phase of the leader connection, showing significant leader branching inside the common streamer zone, are presented for the first time.
3. Positive and negative leader speeds inside the common streamer zone were found to be similar. Higher leader speeds were generally associated with higher leader currents.
4. In the case of head-to-head leader connection, the infrared brightness of the junction region (probably representing the gas temperature and, hence, the energy input) was typically a factor of 5 or so higher than for channel sections either below or above that region.
5. In 16% of cases, the downward negative leader connected to the upward positive leader below its tip (attached to the lateral surface of the positive leader), with the connection being accomplished via a channel segment that appeared to be perpendicular to one or both of the leader channels.

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