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Observations of stepping mechanisms in a rocket-and-wire triggered lightning flash

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[1] We present 10 high-speed video images that depict the bottom 150 m of a downward-negative, dart-stepped leader in a rocket-and-wire triggered flash, recorded at 240 kiloframes per second (4.17 μs frame integration time), along with correlated measurements of the X-ray emission at 50 m, electric field derivative (dE/dt) at 80 m, and the rocket-launch-tower current beneath the leader. We observed discrete segments of secondary channel that exhibited luminosity above that of the surrounding corona streamers and were distinctly separate and beneath the downward-extending leader channel. These segments appear similar to the space stems or space leaders that have been imaged in long negative laboratory sparks. Multiple simultaneous pulses in X-ray emission, dE/dt, and launch tower current were recorded during the time that the leader steps were imaged. The leader extended at an average downward speed between 2.7×10^6 and 3.4×10^6 m s^{-1}.

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1. Introduction

[2] Intermittent progression of downward-propagating, negatively charged stepped and dart-stepped leaders was first reported by *Schonland et al.* [1935], motivating further studies of the development of stepped leaders, including characterization of propagation speeds, step lengths, interstep intervals, and the charges and currents involved [e.g., *Schonland*, 1956; *Berger and Vogelsanger*, 1966; *Orville and Idone*, 1982; *Nagai et al.*, 1982; *Chen et al.*, 1999]. The mechanisms governing individual step formation, however, remain a mystery.

[3] Laboratory spark gaps several meters in length with applied voltages on the order of megavolts have been used to study leader stepping mechanisms through measurement of electrode voltages and currents, and by optically time-resolving the leaders with streak photography. The diagram in Figure 1a illustrates the "streamer zone" of a negative laboratory leader several microseconds after initiation from the high-voltage electrode, as first described by *Gorin et al.* [1976]: (1) primary leader channel that grows from the negative high-voltage electrode, (2) leader tip, (3) positive streamers (filamentary channels of low conductivity), (4) space stem, and (5) negative streamers emanating from the space stem. The streamer zone apparently extends from the primary leader channel intermittently [*Reess et al.*, 1995]. Figure 1b depicts negative leader development in time from left to right, as interpreted via streak photography, with electrode current shown below (Figure 1c). The negative electrode is at the top, and the leader develops downward toward a grounded plane. Numbers 1 through 5 correspond to the descriptions for Figure 1a. The leader tip develops quasi-continuously down curve 2 in Figure 1b, with the space stem moving along the negatively sloped dashed line labeled 4. The space stem eventually thermalizes and becomes a space leader (6) that develops bidirectionally. When the positive end (top) of the space leader merges with the negative leader tip (at 7), the higher potential of the leader channel is transferred to the negative end of the space leader (bottom), followed by a burst of negative corona (mobile, diffuse space charge) or corona streamers (8). At this point, current and luminosity waves travel up the leader channel, completing the leader step. The spark propagation continues in the corona created at 8 with the development of a new space stem that initiates the next leader step. Current pulses in the grounded electrode are associated with each step, shown in Figure 1c. Reports by others [e.g., *Les Renardieres Group*, 1978; *Ortega et al.*, 1994; *Bazelyan and Raizer*, 1998; *Gallimberti et al.*, 2002] have independently confirmed this general description of negative laboratory leader step formation.

[4] The extent to which laboratory leaders resemble lightning leaders is unclear, since the scales of the two in length, voltage, current and time can be considerably different. However, there are several reports of observations of stepped or dart-stepped leaders in lightning that resemble laboratory sparks. *Schonland et al.* [1935] reported faint luminosity extending 30 m below the bottom of a bright negative-leader step near ground in a downward negative flash. *Wang et al.* [1999] reported observations of upward-propagating luminosity waves that originated at newly formed leader steps in a dart-stepped leader in a rocket-and-

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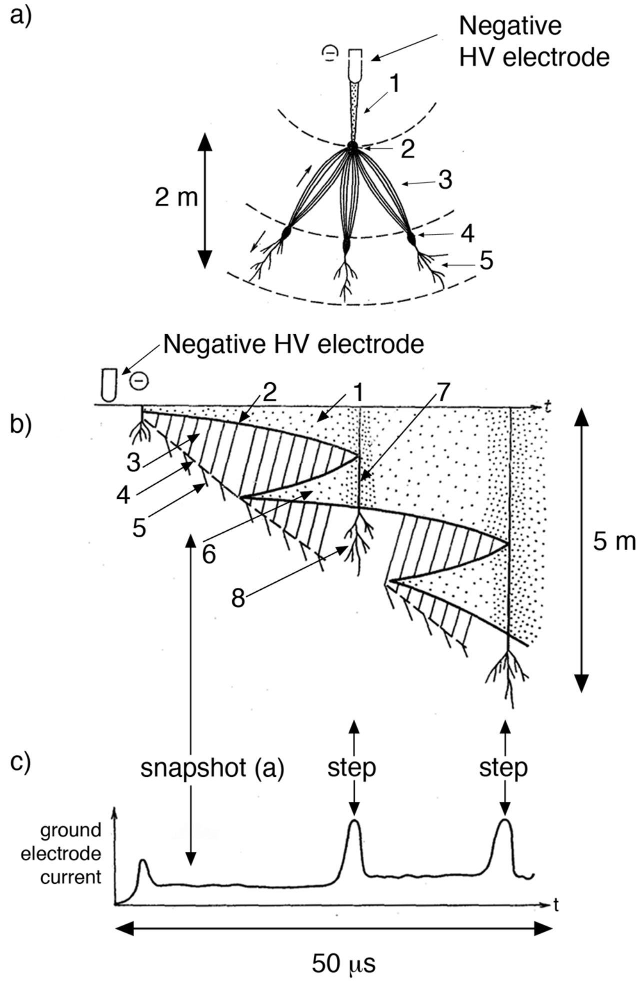

Figure 1. (a) A diagram (snapshot) showing the streamer zone structure ahead of a negative leader tip, (b) a space-time diagram of negative leader development with time increasing from left to right over 50 μs, and (c) the corresponding current in the ground electrode. Diagrams are adapted from *Gorin et al.* [1976].

wire triggered lightning flash [*Rakov and Uman*, 2003]. *Biagi et al.* [2009] reported imaging two space stems that were associated with a dart-stepped leader in a triggered lightning flash. One space stem was of 4 m length and formed at a height of 250 m above ground. The other space stem, depicted in a 20 μs frame in *Biagi et al.*'s [2009] Figure 4, was significantly more luminous than the surrounding corona streamers, was about 2 m in length, and formed about 5 m below the downward negative dart-stepped leader tip and 5 m above the upward positive connecting leader. While *Biagi et al.* [2009] referred to these two luminous channel segments as space stems, they could also be called space leaders, since the latter are more luminous and more spatially developed version of the former.

[5] In this paper we present novel high-speed video observations of development of a negative dart-stepped leader within 150 m of the ground. The high-speed video images clearly show that secondary channels formed separately and ahead of the leader channel in a manner that is similar to space stems and/or space leaders in long laboratory sparks. We relate these images to synchronized measurements of the X-ray emission at 50 m, the electric field derivative at 80 m, and the current in the grounded launch tower, and we discuss the commonality between our observations and the corresponding features of long laboratory sparks.

2. Experiment

[6] High-speed video frames were recorded with a Photron SA1.1 operating at a frame rate of 240 kiloframes per second (kfps), or 4.17 μs per frame, with a resolution of 320 × 48 pixels (vertical × horizontal) and 12-bit amplitude resolution. The camera was located 440 m from the rocket launch tower and had an effective field of view (FOV) of 21 m horizontally and from 11 m to 150 m AGL vertically, and spatial resolution of about 0.44 m. The current in a wire between the aluminum launch tubes and Earth was measured with a noninductive shunt having a resistance of 1.25 mΩ. The current recorded before the downward leader attached to the tower is thought to be primarily the response of the launch tubes and their grounding conductor acting as an electric field derivative (dE/dt) antenna located directly beneath the approaching downward-propagating leader. There may also have been conduction current flow through a weakly conductive channel residue from the previous stroke and/or an upward connecting positive leader. Electric field derivative was recorded at a distance of 80 m from the launch tower using a flat-plate sensor, and X-ray emission was recorded at a distance of 50 m from the launch tower using a 7.6 cm × 7.6 cm $LaBr_3$ scintillator/PMT sensor. The current, dE/dt, and X-ray measurements were digitized with 8-bit vertical resolution at a sampling rate of 250 MHz. Measurements were synchronized using GPS timing, with account taken for the instrumentation time delays, but not the source-to-instrument propagation time, which changes with source location and can be as large as 580 ns. The luminosity recorded in the high-speed video frames may have occurred at any time during the frame integration time, and thus has a timing uncertainty of ±4.17 μs.

3. Results

[7] The measurements presented here are for a downward-negative, dart-stepped leader that preceded the fifth and final stroke of a flash triggered on 29 June 2009 at the International Center for Lightning Research and Testing (ICLRT) in north-central Florida. The fifth stroke occurred about 1.029 s after the first stroke, 361 ms after the fourth stroke and 1.560 s after the triggering wire exploded during the initial stage of the flash. The long time interval between the wire destruction and the fifth stroke makes it unlikely that significant copper residue from the destroyed triggering wire was present along the leader path.

[8] Figure 2 contains a sequence of the 10 high-speed video frames depicting the leader descending from 150 m to 11 m AGL, with time increasing from left to right in 4.17 μs intervals. The frames span about 21 m horizontally, and have heights AGL labeled in 10 m increments. In the first nine frames the leader descended from 150 m

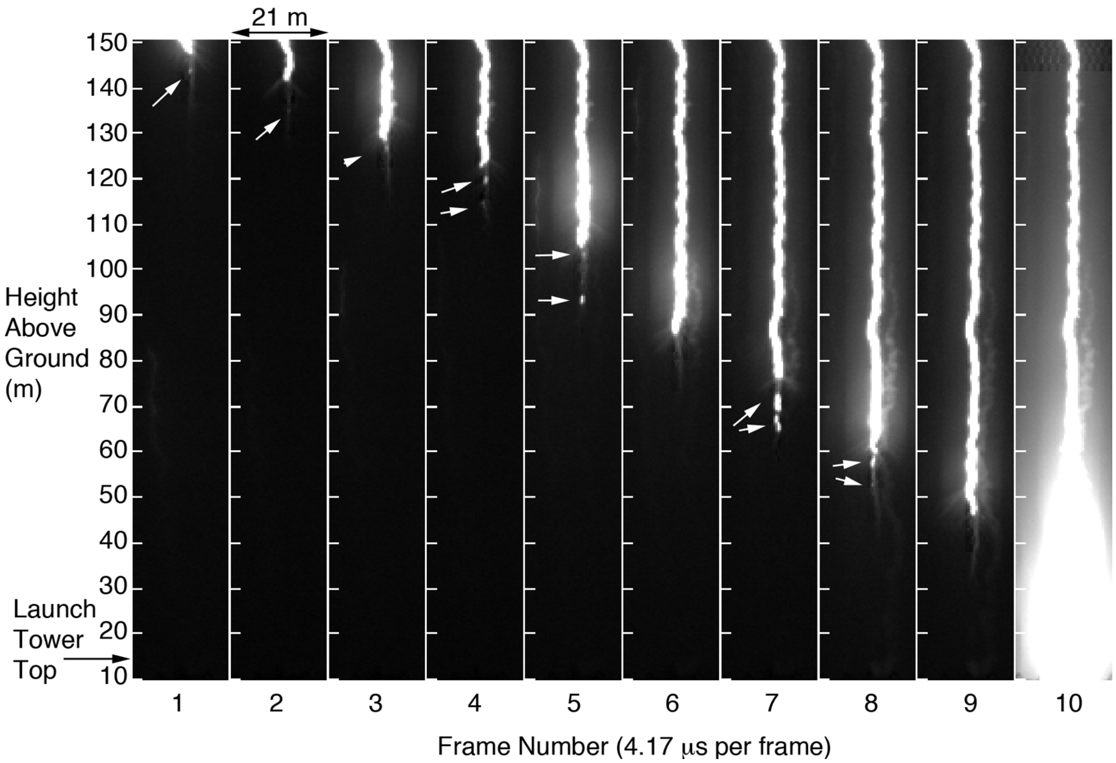

Figure 2. Ten high-speed video frames (240 kfps, 4.17 μs per frame) depicting the leader developing from 150 m height to ground during a time of 41.7 μs. The top of the launch tower is 14 m above ground. The white arrows point to the luminous segments that formed separately from and below the downward-extending leader channel (some of them are too faint to be seen in this reproduction, but are readily identifiable in the original frames, and in Figure 3). The return stroke began during frame 10.

to 47 m with an average speed that was between 2.7×10^6 and 3.4×10^6 m s^{-1}, depending on when the leader first reached 150 m and 46 m during the integration times of frames 1 and 9, respectively. The leader speed may have increased in the lower 45 m of development during the integration of frames 9 and 10, either because the leader accelerated (an actual increase), or because an upward positive connecting leader intercepted the downward leader (an apparent increase), although there is no optical evidence of the latter having occurred. The large increase in luminosity in the lower 40 m seen in frame 10 is from the beginning stage of the upward-propagating return-stroke current wave. Frame 11 (not shown here) was completely saturated by return stroke luminosity.

[9] The features of most interest in Figure 2 are the luminous segments of channel (identified by white arrows) that are 1 to 4 m in length, 1 to 10 m below the leader tip, and separated by darker gaps. The luminous segments ahead of the leader tip in frames 4 (top arrow), 5 (bottom arrow), 7 (both arrows), and 8 (top arrow) had a luminance about equal to that of the leader channel. The other luminous segments in frames 1, 2, 3, 4 (bottom arrow), 5 (top arrow) and 8 (bottom arrow) were less well defined and significantly less luminous than the leader channel, although still more luminous than the surrounding corona streamers. The sections of the frames just below the leader tip are shown expanded and contrast-enhanced in Figure 3. Lower-luminosity corona and forked corona streamers are present in the vicinity of the leader tip that apparently did not develop in a direction greater than 60 degrees from vertical, best seen in the expanded and contrast-enhanced image 2 in Figure 3.

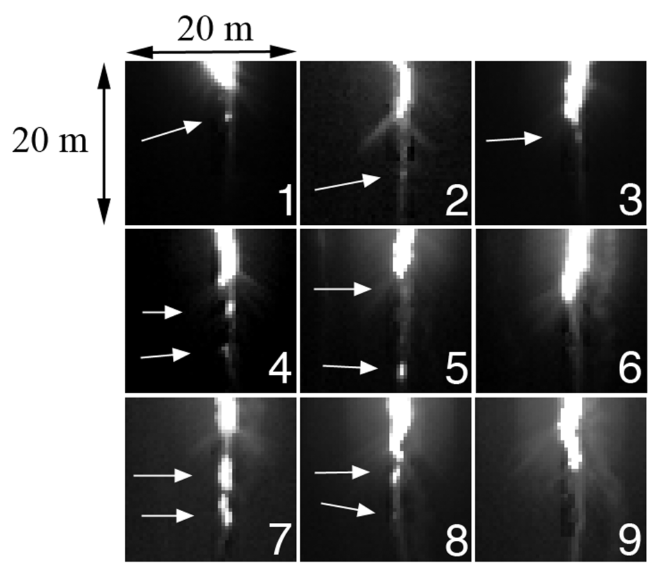

Figure 3. The bottom 20 m of the downward-extending leader channel in the first nine frames in Figure 2, shown expanded and contrast-enhanced. Each image shows about 20 m × 20 m. The white arrows correspond to those in Figure 2 and point to the luminous segments of interest.

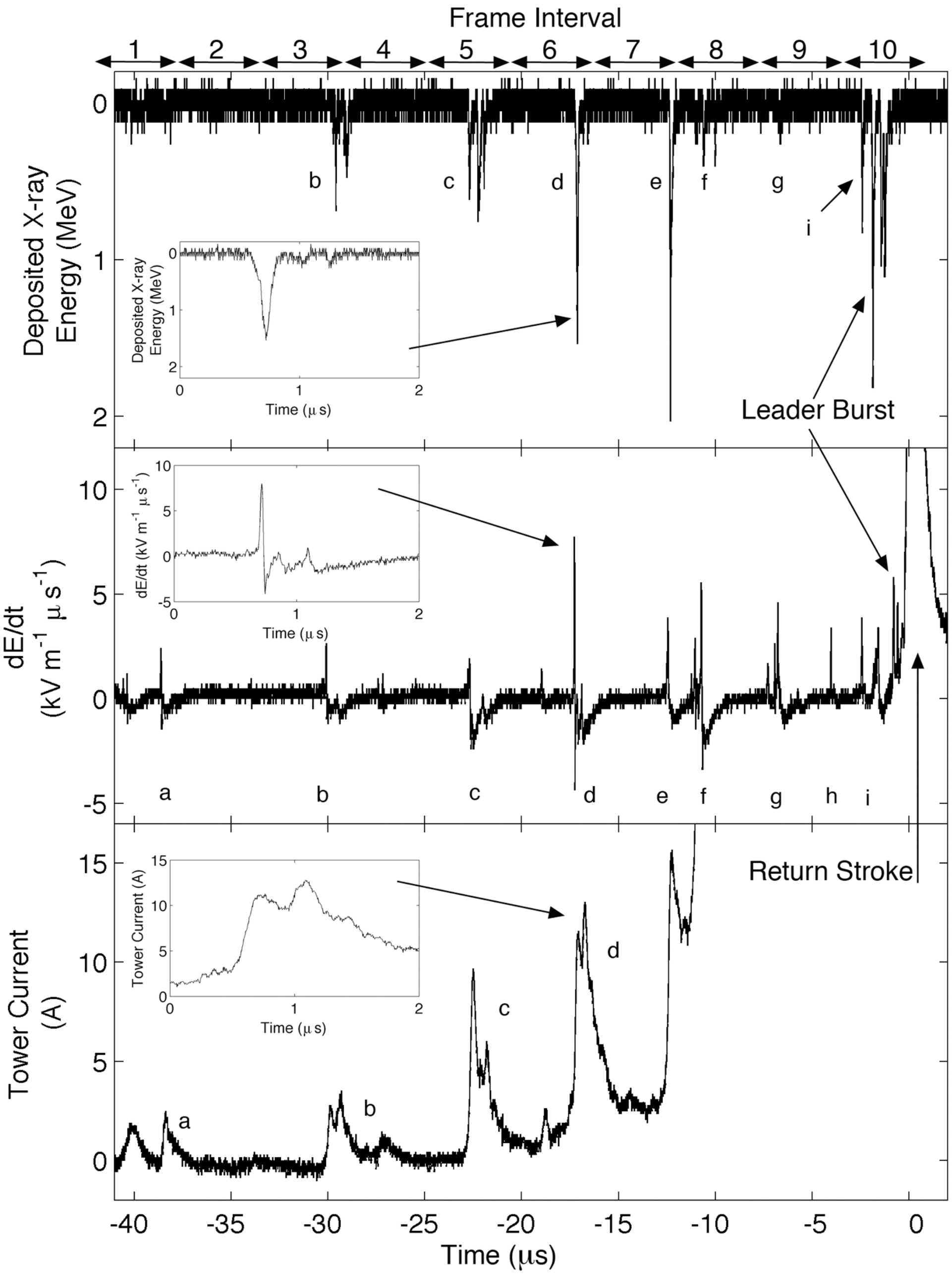

Figure 4. (top) X-ray emission, (middle) dE/dt, and (bottom) tower current displayed on a 42 μs time scale, recorded during the time when the 10 images shown in Figures 2 and 3 were recorded (frame intervals shown at top). The return stroke began at time zero. The inset plots show the pulses that occurred at −17 μs on a 2 μs time scale.

[10] Figure 4 shows the deposited X-ray energy (Figure 4, top), electric field derivative (Figure 4, middle), and launch tower current (Figure 4, bottom) during the time when the 10 high-speed video frames were recorded (frame intervals are shown at the top of Figure 4, ±4.17 μs). Positive dE/dt and current correspond to negative charge moving downward or positive charge moving upward. The return stroke began just after time zero. There were 10 distinct pulses in the dE/dt record that were likely produced by leader steps, and there was a "leader burst" [*Howard et al.*, 2010; *Murray et al.*, 2005] about 1 μs before the return stroke began. In each of the 10 dE/dt pulses, there were one to three secondary peaks following and/or preceding the largest peak. Corresponding current pulses were measured between the launch tubes and ground before the current sensor electronics saturated (at about −10 μs), and each had one to two peaks with timing that matched that of the peaks in dE/dt. A low-amplitude, steady current apparently began to flow after the pulse at −30 μs, due to corona, displacement current and/or an upward leader. Corresponding X-ray pulses were recorded for five of the dE/dt and current pulses, although the timing of the secondary X-ray peaks did

not always match that of the dE/dt peaks. For example, the inset plots in Figure 4 show on a 2 μs time scale a pulse in X-ray, dE/dt, and current that occurred at -17 μs.

4. Discussion

[11] The luminous segments of secondary channel depicted in Figures 2 and 3 that were separated from the primary leader channel by darker gaps have spatial dimensions that are similar to or slightly larger than the space stems and space leaders observed in long laboratory sparks. *Ortega et al.* [1994] reported that space leaders in a 16.7 m gap develop a distance of 1.4 to 2.2 m ahead of leader channels and extend the leader channel by 1 to 5 m. *Les Renardieres Group* [1978] similarly reported that space leaders in 5 m and 7 m gaps develop 1 m to 2.5 m ahead of leader channels and extend the leader channel by about 1 m. In frame 8, two well-defined segments of luminosity appear in series ahead of the leader channel that are about as luminous as the leader channel, suggesting that they were probably space leaders. There were two segments of luminosity ahead of the leader in frames 4, 5, and 7, although it is unclear if these were space stems or space leaders. *Les Renardieres Group* [1978] observed multiple simultaneous space leaders in long laboratory sparks, with the number of space leaders that develop simultaneously increasing with increasing voltage risetimes. *Ortega et al.* [1994] reported the simultaneous development of "several" space leaders from different space stems, in series (colinear) or parallel (side by side), and noted that a space stem may develop into a space leader only if an additional space stem develops further ahead of the leader channel. *Ortega et al.* [1994] reported that current pulses from laboratory leader steps exhibited two distinct peaks when they formed with two space leaders. *Howard et al.* [2010], using a dE/dt time-of-arrival network to locate sources associated with natural and triggered lightning steps with an accuracy on the order of meters, reported that the source location of subsidiary peaks in a single overall leader-step dE/dt pulse were grouped within a few tens of meters, indicating that the causative leader step was formed through a complex series of breakdowns. For the leader presented here, all of the dE/dt pulses that were measured during the time when the leader was imaged had one to three secondary peaks, and the corresponding current pulses had similar peaks. These observations support the interpretation that the luminous segments are space stems or space leaders that were involved in the leader step formation process.

[12] The time coincident X-ray, dE/dt, and current pulses, along with the optical observation of step formation support the well-established fact that X-ray emissions are produced during the leader phase of lightning and are associated with the leader steps [e.g., *Dwyer et al.*, 2004, 2005b; *Howard et al.*, 2008]. The high electric fields of corona streamers that develop from leaders are presently thought to produce cold runaway electrons in streamer tips that cause X-ray emission via bremsstrahlung radiation [*Dwyer*, 2004; *Moss et al.*, 2006]. X-ray emission has also been observed in laboratory sparks smaller than 2 m, but apparently only in association with corona streamer development [*Dwyer et al.*, 2005a; *Rahman et al.*, 2008; *Dwyer et al.*, 2008]. The streamer zone of negative laboratory leaders can be several meters in length, and in gaps shorter than 2 m the streamer zone connects to ground without the development of space leaders [*Gorin et al.*, 1976; *Ortega et al.*, 1994; *Reess et al.*, 1995]. A detailed study of laboratory spark leaders that develop stepwise via the space leader mechanism (gaps greater than 2 m length and with long voltage risetimes) using microsecond or submicrosecond high-speed video and synchronized X-ray measurements might help to clarify when and where X-rays are produced in lightning and long laboratory spark leaders.

[13] If there were 10 steps, as the dE/dt record indicates, then the average step length was about 11 m, which is close to the 5 to 10 m reported by *Orville and Idone* [1982] for steps of dart-stepped leaders in triggered lightning. *Schonland* [1956] reported that leader step lengths in natural dart-stepped leaders near ground were on average 12.7 m, and *Idone and Orville* [1984] reported step lengths of 10 to 30 m. Our average downward dart-stepped leader speed was between 2.7×10^6 and 3.1×10^6 m s^{-1}, which is consistent with the observed range of speeds, between 0.5 and 8×10^6 m s^{-1}, reported for dart-stepped leaders in previous studies [*Schonland*, 1956; *Orville and Idone*, 1982; *Wang et al.*, 1999]. Although it appears likely that the steps in the dart-stepped leader discussed here developed through mechanisms similar to those in long laboratory sparks, it is not clear that such mechanisms operate on the longer spatial scales of stepped leaders in natural lightning, between 10 and 200 m [*Schonland*, 1956; *Berger and Vogelsanger*, 1966; *Chen et al.*, 1999]. We suggest that such longer leader steps may be produced through multiple space leaders developing in series and nearly simultaneously.

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