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Key Points:
- Observations of naturally occurring bidirectional leader initiation and development
- Bidirectional leaders initiate near and connect with previously formed positive leader channels creating new positive branches
- Bipolar leader positive and negative ends behave differently, and the negative end propagates faster than the positive end

Correspondence to:
T. A. Warner,
tom.alan.warner@gmail.com

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Observations of bidirectional lightning leader initiation and development near positive leader channels

Tom A. Warner[1], Marcelo M. F. Saba[2], Carina Schumann[2], John H. Helsdon Jr.[1], and Richard E. Orville[3]

[1]Department of Physics, South Dakota School of Mines and Technology, Rapid City, South Dakota, USA, [2]National Institute for Space Research, INPE, San José dos Campos, Brazil, [3]Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, USA

Abstract Based on the analysis of high-speed optical and electric field change data, we present three observed cases in which a naturally occurring bidirectional lightning leader initiated and developed in virgin air near a previous established positive leader channel. Twice a new leader formed near an upward propagating positive leader that had initiated from a tower during an upward flash and once a new leader formed near a downward propagating positive leader prior to a positive cloud-to-ground return stroke. There were clear and consistent behavioral differences between the positive and negative leader ends of the newly formed bidirectional leader, and the positive end grew more slowly than the negative end in each case. In all three cases, the negative end of the bipolar leader connected with the previously formed positive leader channel creating a new positive leader branch. These rare observations show the bidirectional nature of naturally occurring lightning and suggest that positive leaders can gain branches by connection with newly formed bipolar leaders.

1. Introduction

Heinz Kasemir first proposed that lightning develops as a bidirectional and bipolar leader [*Kasemir*, 1960]. In the late 1980s and early 1990s, analysis of aircraft-initiated lightning observations supported this theory [*Fischer et al.*, 1985; *Mazur*, 1989a, 1989b; *Laroche et al.*, 1991]. Lightning Mapping Arrays (LMAs) are able to map lightning leader development by the triangulation of VHF emitted radiation during breakdown; however, a single source point is determined in each observation window [*Rison et al.*, 1999; *Krehbiel et al.*, 2000; *Thomas et al.*, 2004]. Even though an LMA can detect breakdown from both positive and negative breakdown [*Edens et al.*, 2012], negative breakdown tends to radiate more strongly at VHF frequencies and can dominate received signals, thereby masking positive breakdown that may be occurring simultaneously. Even so, the bipolar nature of lightning leader development can be visualized through LMA observations [*Krehbiel et al.*, 2008]. Single-point electric field sensing instrumentation such as fast and slow antenna systems and electric field meters record the electric field change resulting from the combined polarities of leader development when occurring simultaneously. However, the spatial location difference between the positive and negative ends relative to the instrument can cause received signals to be dominated by the closest polarity [*MacGorman and Rust*, 1998, section 6]. Therefore, observing bipolar breakdown in naturally occurring lightning has proven challenging.

Based on the analysis of high-speed video observations and electric field change data, it was proposed that recoil leaders develop in a bidirectional manner along decayed positive leader branches [*Mazur et al.*, 2013; *Warner et al.*, 2012a, 2012b; *Saba et al.*, 2013]. In the case of an upward positive leader initiated during upward lightning or following the return stroke of a negative cloud-to-ground flash, the negative end of the recoil leader on a decayed positive leader branch can travel back to the branch point of a still conductive positive leader channel and result in an M-component upon connection. Or if the main positive leader channel has decayed, the negative end of the recoil leader can retrace the main channel path to ground as a dart leader resulting in a subsequent return stroke. The positive end of the recoil leader travels outward along the decayed positive leader branch illuminating and extending the tip of the branch. In the case of recoil leaders, however, their formation occurs on previously formed leader channels.

Recently, *Montanyà et al.* [2015] reported on a high-speed video observation of bidirectional leader development near a previously formed lightning channel. Instead of initiating on a previously formed channel path that had decayed, the leader developed as bidirectional breakdown of virgin air and the negative end of the leader connected with a previously formed positive leader channel that was nearby. Analysis of the high-speed video using two-dimensional photogrammetry and visual characterization showed

1. The positive and negative ends of the bidirectional leader began simultaneously within the 90–180 μs time resolution of the high-speed video recordings.
2. The positive leader end formed a single nonbranched channel, while the negative leader end was branched.
3. The single positive leader channel was visible all the time and was brighter than the multiple negative leader branches.
4. Both leader tips were brighter than their trailing channels, but the leader tip luminosity decreased as the bidirectional leader expanded.
5. The speed of the positive leader end was a factor of 2 lower than the average speed of the negative leader end.
6. Both ends of the bidirectional leader exhibited their highest speeds during the first millisecond.
7. After the first millisecond, the speed of the positive leader end decreased faster than the negative leader end.
8. Upon connection by one of the negative leader branches with the nearby positive leader channel, a "return stroke-like" luminosity increase traveled along the length of the negative leader branch to the leader origin point. This was followed by additional illumination of active nonconnected negative branches and the positive end of the leader.
9. After connection, the former bipolar leader served as a newly connected positive leader branch and continued to grow, exhibiting only positive leader characteristics.

Most recently, *Tran and Rakov* [2016] reported on high-speed video and electric field observations of bidirectional leader development associated with an initial cloud flash. In this case, redevelopment along a decayed intracloud leader channel segment transitioned to bidirectional leader growth in virgin air. The negative end of the bidirectional development traveled to ground resulting in a negative stepped leader/return stroke sequence.

In this paper we report on three similar observations to those reported by *Montanyà et al.* [2015], in which a bidirectional leader formed near an actively growing positive leader channel, and in all three cases, the negative end of the new leader connected with the existing positive channel forming a new positive leader branch. In two cases a new leader bipolar leader developed near an upward propagating positive leader during an upward flash from a tower, and in one case a new leader formed near a downward propagating positive leader during a positive cloud-to-ground flash prior to a positive cloud-to-ground return stroke (+CGRS). These observations were made with high-speed video cameras, and in two of the cases, fast antenna electric field change instrumentation.

2. Instrumentation

Since 2008, multiple high-speed video cameras and electric field sensing instrumentation have been used to record lightning activity around Rapid City, SD, USA. Although the focus of the research was upward lightning from tall towers [*Warner et al.*, 2012a, 2013], all lightning activity was recorded when in the area. The high-speed cameras recorded between 1000 and 100,000 images per second (ips), utilizing monochrome sensors with 12-bit dynamic range.

From 2011 to 2014, the National Institute for Space Research (INPE), Brazil, operated flat-plate, fast antenna systems with a sample rate of 5×10^6 samples/s and a lower and upper frequency bandwidth of 306 Hz and 1.5 MHz, respectively. Multiple gain systems were deployed at two locations to optimize observations of triggering and upward flash leader development from 10 towers located in Rapid City.

3. Observations

3.1. 16 July 2009, 07:19:12 UT

On 16 July 2009 at 07:19:12 UT, an upward positive leader (UPL) developed from a tower in Rapid City, SD, triggered by a nearby +CGRS. Two high-speed cameras operating at 7207 and 54,001 ips (139 μs and 18 μs exposures, respectively), 7.15 km from the tower, recorded the upward flash. The UPL grew vertically without

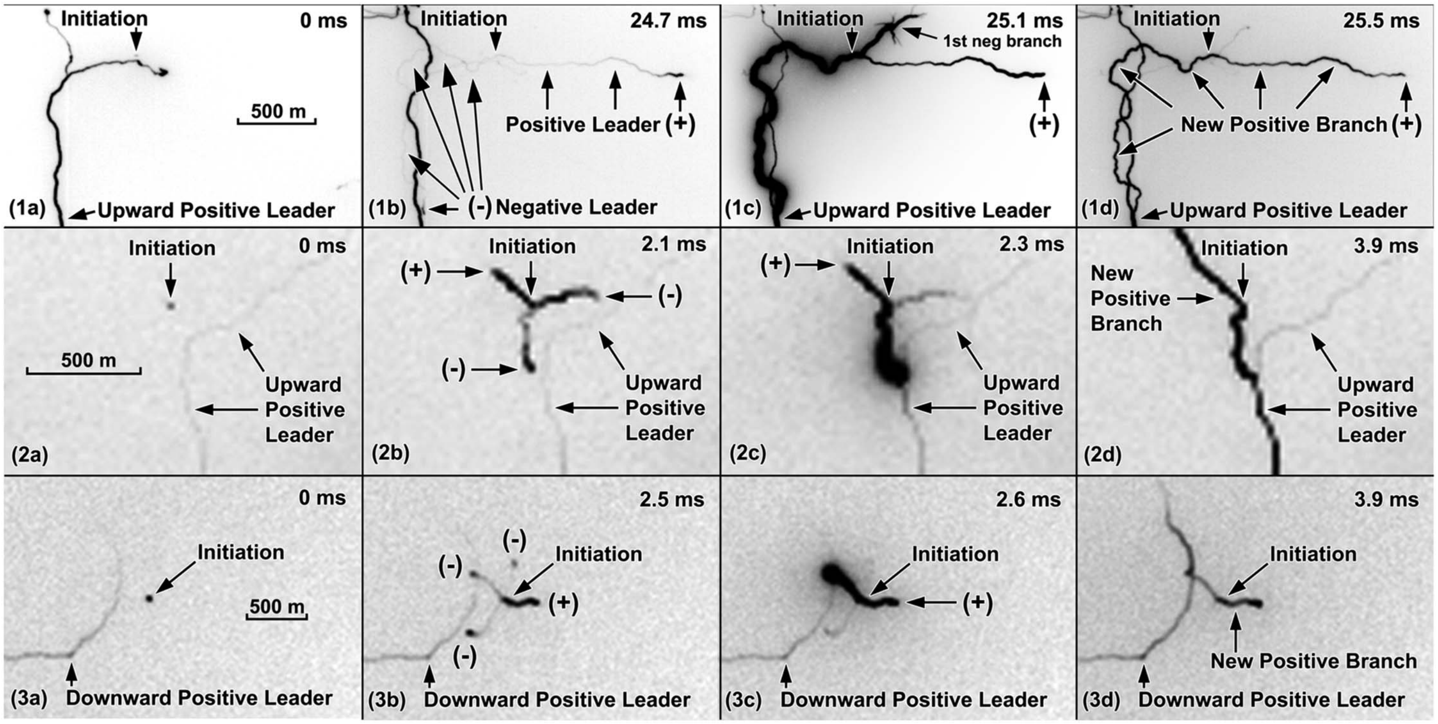

Figure 1. High-speed video images from the three cases (1–16 July 2009, 2–6 July 2011, and 3–28 May 2013) showing (a) the initiation of a bidirectional leader near a previously formed positive leader channel, (b) the new leader just prior to the negative end connection with the positive channel, (c) the connection of the negative end of the leader with the positive channel, and (d) the newly connected positive leader branch.

branching for 17.2 ms, at which point the UPL transitioned to horizontal propagation at an estimated height of 1.9 km. At 30.7 ms after UPL initiation, a bidirectional leader formed 33 m from the main UPL channel back along the segment, where it had transitioned to horizontal propagation as shown in Figure 1a1. The positive end grew without branching and propagated in a relatively straight horizontal path while maintaining a fairly constant luminosity. However, there were noticeable luminosity variations during the first few milliseconds of its formation. The negative end, however, propagated more erratically, was not as bright as the positive end and developed five branches before it connected with the UPL. The first negative leader branch formed back at the bipolar leader initiation point 4.4 ms after initiation and with the main negative end already 301 m in length. The remaining four branches formed at the tip of the advancing negative leader. The negative end branch tips brightened frequently characteristic of stepping behavior but were not as bright as the tip of the positive end. The trailing negative leader channels were the least luminous portions of the bidirectional leader. Initially, the negative end propagated horizontal away and in an opposite direction from the positive end for 8.9 ms (551 m) before turning vertically downward (based on two-dimensional analysis). It continued downward for 15.9 ms and then connected with the UPL at a height of 0.9 km above the tower tip, 1.0 km below the height of its initial formation. Only the camera operating at 7207 ips captured the new leader initiation due to a wider field of view. However, both cameras captured the connection. Figure 1b1 shows the high-speed video image just prior to the bipolar leader negative end connection with the UPL.

Upon connection 24.8 ms after the bidirectional leader formed and 55.5 ms after UPL initiation, rapidly expanding luminosity traveled up from the connection point through the negative end of the bipolar leader, past the initiation point and out to the positive end. Figure 1c1 shows the newly connected leader 0.3 ms after connection. There was a subtle but distinct luminosity difference between the positive and negative portions of the bipolar leader upon connection with a slightly higher brightness visible from the connection point to the initiation point and out the first branch. Simultaneously upon connection, luminosity increased from the connection point on the UPL channel downward to the tower tip. However, the luminosity increase in the main channel was less than that along the newly connected leader. After the luminosity of the newly connected branched decayed to a level similar to the main UPL as seen in Figure 1d1, the newly attached

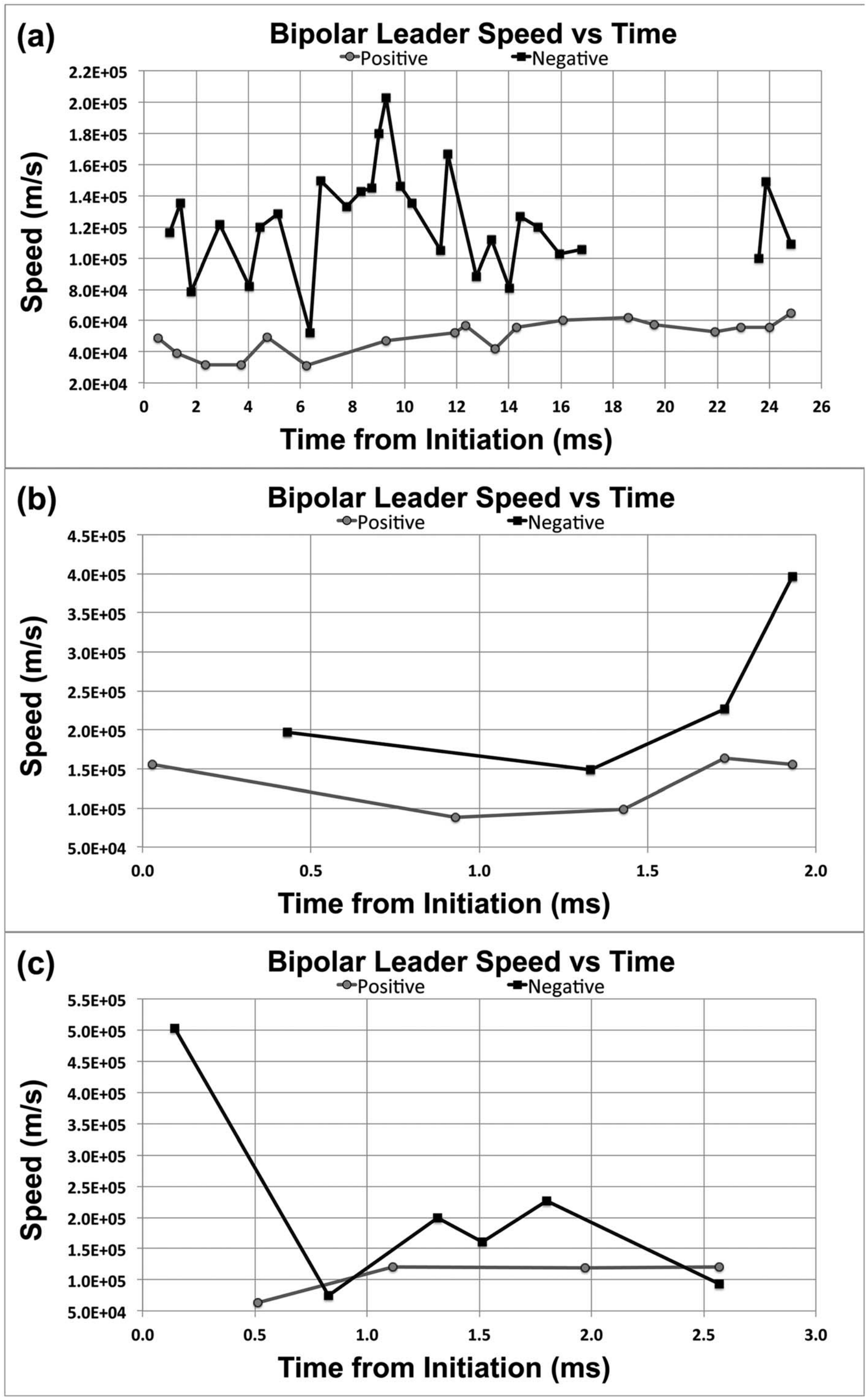

Figure 2. Plot of the measured speeds of both the positive (gray with circle data points) and negative (black with square data points) end of the bidirectional leaders that developed near a positive leader channel on (a) 16 July 2009, (b) 6 July 2011, and (c) 28 May 2013.

Table 1. Bipolar Leader Speeds

Date	Minimum (ms^{-1})	Average (ms^{-1})	Maximum (ms^{-1})
16 July 2009			
Negative	0.52×10^5	1.23×10^5	2.03×10^5
Positive	0.31×10^5	0.50×10^5	0.65×10^5
Difference	0.21×10^5	0.73×10^5	1.38×10^5
Factor	1.7	2.5	3.1
6 July 2011			
Negative	1.49×10^5	2.42×10^5	3.97×10^5
Positive	0.88×10^5	1.32×10^5	1.64×10^5
Difference	0.61×10^5	1.10×10^5	2.33×10^5
Factor	1.7	1.8	2.4
28 May 2013			
Negative	0.74×10^5	2.09×10^5	5.03×10^5
Positive	0.63×10^5	1.05×10^5	1.20×10^5
Difference	0.11×10^5	1.04×10^5	3.83×10^5
Factor	1.2	2.0	4.2

branch continued to grow similarly to that seen by the positive end prior to connection (i.e., continuously with little deviation in direction).

Two-dimensional photogrammetry measurements were made to determine leader speeds and lengths. Prior to the bipolar leader's connection with the main UPL channel, the positive end of the bipolar leader reached a length of 1.23 km at an average speed of 0.50×10^5 ms^{-1}. The negative end extended a total length of 1.83 km at an average speed of 1.23×10^5 ms^{-1} (2.5 times faster than the positive end). Therefore, the total length of the bipolar leader was 3.06 km before it connected to the UPL.

Figure 2a shows a graph of the measured bidirectional leader speeds. The negative leader maintained a higher speed throughout its development with more variation in speeds between measurements. The minimum and maximum recorded negative leader speeds were 0.52×10^5 ms^{-1} and 2.03×10^5 ms^{-1}, respectively. The gap in negative leader measured speeds between 16.8 ms and 23.0 ms was due to a temporary decay of the connecting negative leader branch, while other negative branches continued to grow. The leader positive end grew at a slower speed than the negative end, and the speed varied less. There was a speed decrease in the first 2 ms followed by a gradual speed increase during the remainder of development. The highest positive leader speed was obtained just prior to connection by the negative end. The minimum and maximum recorded positive leader speeds were 0.31×10^5 ms^{-1} and 0.65×10^5 ms^{-1}, respectively. Table 1 summarizes the measured leader speeds and differences.

3.2. 6 July 2011, 17:00:18 UT

On 6 July 2011 at 17:00:18 UT, an UPL developed from a tower in response to preceding intracloud negative leader activity that passed near the tower. The flash was observed with two high-speed cameras operating at 10,000 and 100,000 ips (100 μs and 10 μs exposures, respectively), 7.15 km from the tower. The UPL grew vertically without branching before transitioning to horizontal propagation 10 ms after its initiation at an estimated height of 1.9 km above the tower tip. At 55 ms after UPL initiation, a bidirectional leader initiated 155 m from the UPL near the point where it transitioned to horizontal propagation as shown in Figure 1a2. Based on analysis from 100,000 ips camera recording with a 22 m per pixel resolution and 10 μs exposures, the initial bright spot that marked the first evidence of leader formation faded and reilluminated 3 times before extending bidirectionally in a continuous manner. Each reillumination presented a slight larger area of brightness, and the second and third reillumination progressed from the negative to the positive end of the leader coincident with an apparent leader step formation on the negative end. Table 2 shows a breakdown of the timing and intervals observed during the initial formation of the leader. Once established, the positive end traveled away from the UPL, did not branch, and maintain a fairly constant luminosity while propagating. The negative end branched forming two main branches at the initiation point as seen in Figure 1b2. One other branch formed on one of the two initial negative branches but decayed shortly after forming. The two branches exhibited luminosity pulses characteristic of stepping at their individual branch tips. At 2.26 ms after the leader initiation, one of the negative end branches connected with the main UPL channel as seen in

Table 2. Bipolar Leader Initiation Pulses, 6 July 2011, Case 2

Observation	Time (s)	Time from Previous Event (μs)	Time from First Illumination (μs)
First illumination	18.662770	0	0
First fade	18.662790	20	20
Second illumination	18.662820	30	50
Second fade	18.662860	40	90
Third illumination	18.662900	40	130
Third fade	18.662990	90	220
Fourth illumination	18.663000	10	230
First branch	18.663030	30	260

Figure 1c2. A bright luminosity increase front traveled from the connection point outward through the negative end of the bipolar leader, past the initiation point, and out to the positive end of the leader. The other negative branch also brightened with the arrival of the luminosity front associated with connection. Likewise, a bright luminosity increase traveled from the connection point down the main UPL channel to the tower tip at an average speed of 3.47×10^7 ms^{-1}, and an even brighter return luminosity front traveled back up the main channel to the branch point and out the newly connected branch to the branch tip at an average speed of 7.35×10^7 ms^{-1}, causing a secondary luminosity maximum in the newly connected branch. After luminosity decay to a level similar to that prior to connection, the newly connected branch continued to propagate as a positive leader for the remainder of the UPL duration as shown in Figure 1d2.

An INPE fast antenna system located 7 km southwest of the tower recorded the field change associated with the upward flash and leader connection. Analysis of the data showed a negative field change pulse (physics sign convention [*Rakov and Uman*, 2003, section 1.4.2]) correlated with the connection of the negative end of the bipolar leader with the UPL as shown in Figure 3a. This was followed by a period of negative field change corresponding to the addition and growth of the UPL and newly connected branch. There was no discernable electric field change deviation outside the noise threshold of the recording system at the time of the bidirectional leader initiation as seen in Figure 3a.

Two-dimensional speed and distance analysis indicated that the positive end of the bipolar leader grew to a length of 202 m prior to connection with an average speed of 1.32×10^5 ms^{-1}, whereas the negative end which included the branch that connected with the main channel reached a length of 357 m with an average speed of 2.42×10^5 ms^{-1} (1.8 times faster than the positive end). Figure 2b shows a plot of the measured speeds for each end of the bidirectional leader, and Table 1 summarizes the measured leader speeds and differences.

3.3. 28 May 2013, 00:29:50 UT

On 28 May 2013 at 00:29:50 UT, a +CG flash occurred south of Rapid City, SD. During the downward propagation of a positive leader that had emerged below cloud base, a bidirectional leader formed 259 m from the positive leader and the negative end of the bipolar leader connected with the downward positive leader forming a new positive leader branch. The main positive leader channel to which the new leader attached continued toward and connected with the ground causing a +CGRS. The National Lightning Detection Network [*Cummins and Murphy*, 2009] recorded a correlated +52.3 kA estimated peak current return stroke, 23.0 ms after the connection of the new bipolar leader.

The flash was observed with three high-speed cameras operating at 1000, 35,000, and 35,015 ips, all positioned 15.9 km northwest of the +CGRS based on the National Lightning Detection Network-indicated location. Analysis of the high-speed video imagery showed that the new bidirectional leader developed from a single point as seen in Figure 1a3 with a nonbranched, continuously propagating positive end traveling away from the main positive leader channel and the negative end branching immediately following initiation. Up to seven branches were visible on the negative end with three of these branches dominating as shown in Figure 1b3. The tips of the negative branches were bright relative to the following negative leader segments and pulsed indicative of stepping. The bidirectional leader positive end luminosity, along with its trailing positive leader segment, remained higher than all of the negative branches.

At 2.62 ms after initiation, one of the bidirectional leader negative branches connected with the main positive leader channel as shown in Figure 1c3, and a bright luminosity increase traveled from the connection point

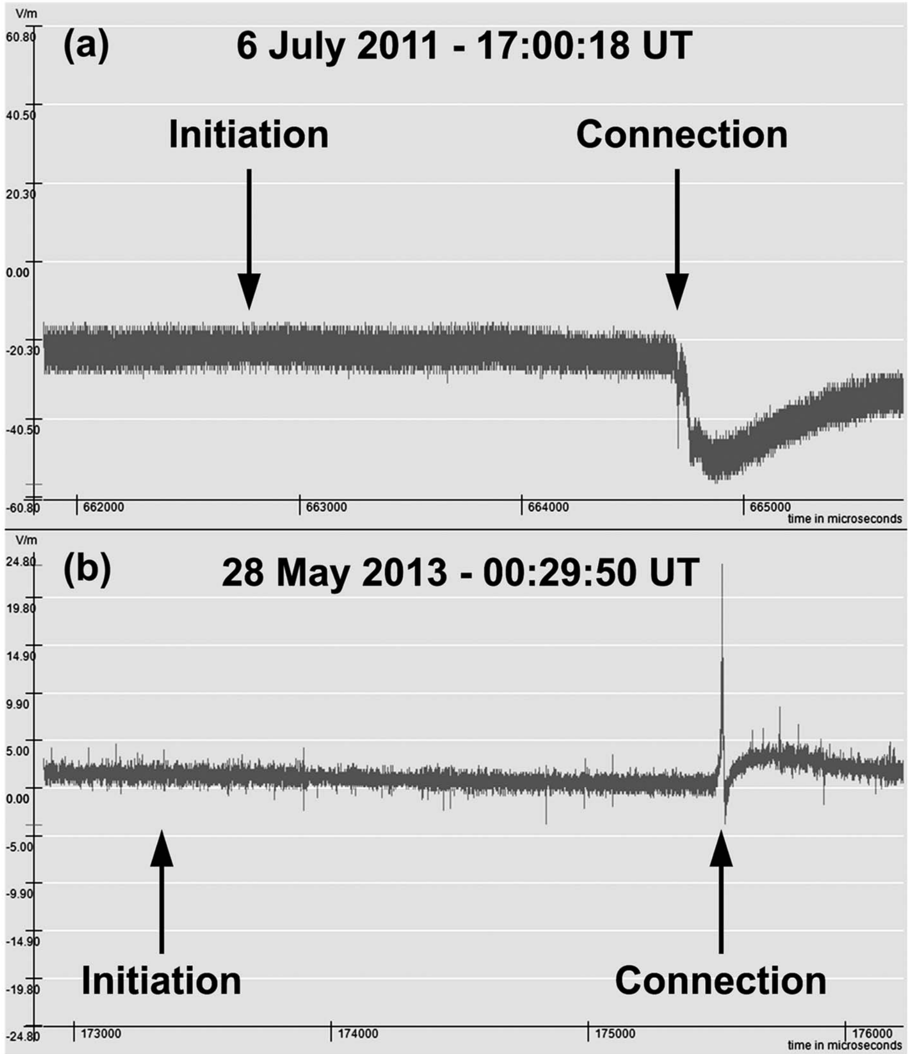

Figure 3. Fast antenna electric field change data trace from (a) 6 July 2011 and (b) 28 May 2013 showing the electric field change associated with the initiation and connection of a bidirectional leader with a previously formed positive leader channel.

toward and past the initiation point and out to the positive end of the leader. Simultaneously, a luminosity increase of lesser magnitude traveled from the connection point along the main positive channel upward toward the cloud base and flash origin. Some brightening of the main positive channel downward from the connection point was also noted, but its brightness was less than the brightness increase along the upper segment. After the connection, the luminosity along the main downward propagating positive leader returned to a level similar to that prior to the connection as shown in Figure 1d3. The newly connected leader continued to grow as a positive leader branch until the +CGRS.

An INPE fast antenna system located 18 km northwest of the +CGRS recorded a positive field change pulse coincident with the connection of the bipolar leader with the main positive channel. This pulse had a bipolar nature as it briefly exhibited a small negative field change following the positive field change peak as seen in Figure 3b. This was followed by a period of slowly varying positive field change due to the connection of an additional positive leader branch and continued downward development of the leader activity prior to the +CGRS. Notice that the bipolar leader connection with a downward propagating positive leader caused an electric field change opposite to that reported in the previous case, where a bipolar leader connected with an upward propagating positive leader. As in the previous case, there was no clearly apparent electric field change deviation beyond the noise threshold of the sensor at the time of bidirectional leader initiation.

Two-dimensional speeds were measured for the positive and negative leader ends. The bipolar leader positive end average speed was 1.05×10^5 ms^{-1}, whereas the negative end exhibited a higher speed with an average of 2.09×10^5 ms^{-1} (2.0 times faster than the positive end). The length of the negative end prior to connection was 370 m, and the positive leader length was 295 m. Figure 2c shows a plot of the measured speeds for each end of the bidirectional leader, and Table 1 summarizes the measured leader speed extremes and differences.

4. Discussion

For all three cases presented in this paper, a bidirectional leader formed near a previous established positive leader channel and the negative end of the newly formed bipolar leader connected with the positive channel creating a new positive leader branch. In each case, the bipolar leader positive end did not branch and propagated in a nearly continuous fashion while maintaining a fairly straight path. For two of the three cases, the negative end of the leader branched immediately following initiation. Whereas in the one other case, the negative end branched once at the initiation point 4.4 ms after initiation and with the negative end already extended 301 m from the initiation point, and then the leader negative branched four additional times at the negative leader tip.

For the two cases where the new leader formed near an established UPL, the leader formed after and near the point where the UPL had transitioned to horizontal propagation just below cloud base. UPLs frequently transition to horizontal propagation near cloud base [*Warner et al.*, 2012b; *Saba et al.*, 2012], and it is likely that this transition results from the presence of a horizontally stratified negative potential well [*Coleman et al.*, 2003, 2008] just below cloud base (e.g., negative charge screening layer or negatively charged rain). It is possible that the electric field is maximized near the area where positive leader channels transition to horizontal propagation, thus creating conditions favorable for a new bipolar leader to form nearby.

Even with the previously mentioned scenario, the possibly unique characteristics of the electric field environment near previously formed positive leader channels when new bidirectional leaders form is unclear, especially given the fact that we have yet to see similar development near previously formed negative leader channels. Given the relatively close proximity of the bidirectional leader initiation to preexisting positive channels could also suggest that the air near the channels may not be completely virgin. It may be poorly conductive due to weak positive leader branching or streamer activity that goes undetected by the high-speed cameras. However, the observed behavior by both ends of the bidirectional leaders is consistent with and exhibits no traits that differ from breakdown of virgin air based on the authors' cumulative analysis of over 500 high-speed recordings of entire flashes, which contain both initial leader breakdown as well as redevelopment on previously ionized channels.

Rison et al. [2016] suggested that many or possibly all lightning flashes are initiated by fast positive breakdown. This fast positive breakdown is limited in spatial extent and occurs in localized regions of intense electric field. Furthermore, the breakdown does not produce a conducting channel but rather a distributed system of positive streamers or streamer-like activity. Slow leader development in virgin air follows the fast positive breakdown once it traverses the locally intense electric field region. Fast positive breakdown has been observed with preceding lightning flash activity. It was observed propagating away from a newly connected negative return stroke channel, which induces positive charge and ground potential along the channel inside storm negative charge regions resulting in locally enhanced electric fields [*Shao et al.*, 1995]. Could the apparent preferential initiation and development of bidirectional leaders near previously established positive leader channels be due to fast positive breakdown initiating in areas of intense electric field where the positive leader channels have traversed through concentrated negative charge regions? Mapping fast positive breakdown in relation to optically observed bidirectional leader development would be necessary to address this possibility.

Yoshida et al. [2012], based on analysis of VHF interferometry data during rocket-triggered lightning research, suggested that new leaders can form near established UPL main channels and branches and can connect to these previously formed leaders creating new branches. Although their data recorded the progression of the negative end of the new leaders that formed, it is likely that these were bidirectional leaders forming near established positive channels like those presented in this paper and previously by *Montanyà et al.* [2015].

In comparison with the bidirectional leader reported by *Montanyà et al.* [2015], there are clear similarities. For all three cases reported here, the leader initiated at a single point and both ends emerged from this point. However, there was evidence from the case recorded at 100,000 ips that early negative leader steps served to reilluminate the positive end until the positive end continued independently (see Table 2). For all three cases, the negative end of the bidirectional leader on average propagated faster than the positive end based on two-dimensional photogrammetric analysis (see Table 1 and Figure 2). Unlike positive leader behavior reported in *Montanyà et al.* [2015], the maximum positive leader speed did not occur immediately after initiation. Rather, the maximum positive leader speeds were achieved prior to connection by the negative end of the leader as seen in Figure 2. Similarly, for the other cases, the speed did not decrease with time like that reported by *Montanyà et al.* [2015].

For all cases, both leader end tips were brighter than the trailing leader segments, but the positive leader trailing segment was noticeably brighter than the trailing segments of the negative leader branches. The luminosity difference between the positive and negative leader segments transitioned at the initiation point and appeared to remain fixed throughout development of the bidirectional leader, suggesting that the neutral point of the bipolar also remained fixed during development. Furthermore, the luminosity of the leader ends did not decrease as the bipolar leader expanded like that observed by *Montanyà et al.* [2015].

For all three cases observed in Rapid City, the luminosity increase that originated at the connection point traveled through the negative segment of the bipolar leader and continued past the leader origin point and out to the tip of the positive end resulting in a brightness increase along the entire newly connected leader branch. Even with camera recording sensitivity reduced to the lowest possible level during analysis, the entire bipolar leader segment's luminosity increased upon connection.

The three cases of bidirectional leader development near a previously formed positive leader channel presented in this paper, along with the similar case previously reported by *Montanyà et al.* [2015], establish an admittedly limited, but yet convincing observation set, which shows naturally occurring lightning's bipolar and bidirectional nature. Analyses of these observations also highlight the asymmetry between positive and negative leader behavior as discussed by *Williams* [2006]. The clear optically observed behavioral difference between the positive and negative ends, and the fact that in all cases, the negative end connected with a previously established positive channel, shows consistent behavior and suggests that the electric field environment near positive leaders can be conducive to the initiation of new leaders and in turn, to the eventual connection of new branches. Just how often new positive leader branches form in this manner and what specific conditions prove favorable should be a focus of future research.

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