AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE
10.1002/2013JD021221

Key Points:
- High-speed video and electric field observations of type β_2 stepped leaders
- Evidences suggest that the "dart streamers" are initiated by recoil leaders
- Type β_2 stepped leaders are explained in the bidirectional leader context

Correspondence to:
L. Z. S. Campos,
leandro.zanella@gmail.com

Citation:
Campos, L. Z. S., M. M. F. Saba, and E. P. Krider (2014), On β_2 stepped leaders in negative cloud-to-ground lightning, *J. Geophys. Res. Atmos.*, *119*, 6749–6767, doi:10.1002/2013JD021221.

Received 19 NOV 2013
Accepted 30 MAR 2014
Accepted article online 2 APR 2014
Published online 13 JUN 2014

On β_2 stepped leaders in negative cloud-to-ground lightning

Leandro Z. S. Campos[1], Marcelo M. F. Saba[1], and E. Philip Krider[2]

[1]INPE—National Institute for Space Research, São José dos Campos, São Paulo, Brazil, [2]Institute of Atmospheric Physics, University of Arizona, Tucson, Arizona, USA

Abstract In their seminal lightning studies using streak cameras, Schonland et al. (1938) identified four negative stepped leader events that they term "β_2," a "rather rare variant of the type β leader", and in it, "the second and slower stage of the leader is associated with the appearance of one or more fast dart streamers, which travel rapidly down from the cloud along the previously formed track and cease when they have caught up with the slower leader tip." Seven negative downward leaders that agreed with the description given by Schonland et al. for type β_2 were recorded in Tucson, Arizona, USA, and in São José dos Campos, São Paulo, Brazil. All cases were recorded by a high-speed camera operating at 4000 frames per second, and electric field changes were measured for three of them. Their "dart streamers" had speeds between 10^6 and 10^7 m s^{-1}, compatible with previous observations of recoil leaders (RLs). Also, during the development of the three cases with correlated electric field changes, it was possible to identify sequences of microsecond-scale pulses preceding the propagation of a dart streamer in the channel. It is proposed that the luminous process that occurs during the development of a type β_2 stepped leader is the visible manifestation of one or more RLs that begin inside the cloud and connect to the in-cloud, positive portion of the bipolar, bidirectional leader, and then travel downward to the lower end of the negative stepped leader path.

1. Introduction

The first return stroke in a flash and the subsequent strokes that create a new ground termination in negative cloud-to-ground (−CG) lightning are initiated by stepped leaders that develop intermittently in the form of faint individual steps, hence the terminology. Based on his seminal streak camera studies of lightning, *Schonland* [1938] classified negative stepped leaders into two categories: α type and β type. Type α leaders propagate with uniform downward speeds, on the order of 10^5 m s^{-1} and have steps that show only small variations in length and brightness. Type α was also the most common type observed, representing 55–70% of all cases reported by *Schonland* [1938, 1956]. Type β leaders on the other hand have a discontinuity in their downward development. In the first phase, near the cloud base, a type β leader has brighter and longer steps compared to the type α and a higher speed of development, on the order of 10^6 m s^{-1}. In the second phase, as it approaches the ground, a type β leader behaves like an α leader, decreasing in speed and brightness and having shorter steps.

In addition, *Schonland et al.* [1938] further classified the type β leaders into two variants: subtypes β_1 and β_2. The type β_1 leader is the most common, and it is basically the same type β leader described in the preceding paragraph. Type β_2 is a "rather rare variant of the type β leader," and in it, "the second and slower stage of the leader is associated with the appearance of one or more fast dart streamers, which travel rapidly down from the cloud along the previously formed track and cease when they have caught up with the slower leader tip" [*Schonland et al.*, 1938, pp. 459–460]. Schonland et al. report only four cases of these events: two showed one dart streamer, one showed two, and one was not detailed in their work. Two of the four events showed an increase in the average leader speed after the dart streamer occurred (flashes 32 and 102), one had a decrease (flash 92), and one did not exhibit any measurable change in speed (flash BX) [*Schonland et al.*, 1938, Figure 9]. In only one case, the dart streamer speed could be estimated, and it was faster than 2.0×10^6 m s^{-1} [*Schonland et al.*, 1938, p. 461]. *Workman et al.* [1936, Figure 1] likely made the first photograph of the type β_2 phenomenon using a slowly moving film camera, and *Schonland et al.* [1938, p. 464] referred to it as a "valuable illustration of the type β_2."

Recently, *Rakov and Uman* [2003, p. 123] have noted that no β_2 cases have been reported in later photographic studies [e.g., *Berger and Vogelsanger*, 1966; *Orville and Idone*, 1982; *Jordan*, 1990]. Possible

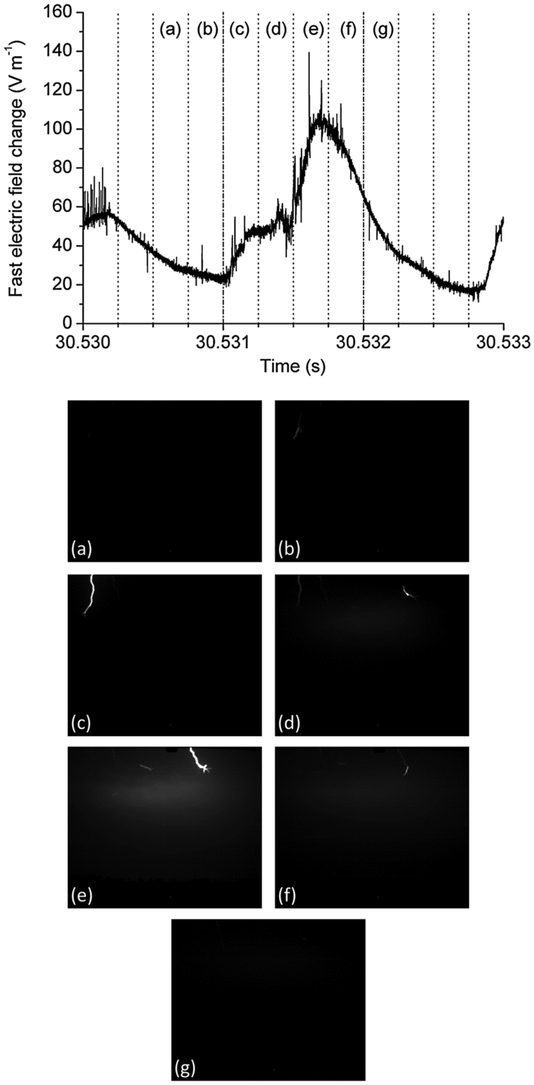

Figure 1. Detailed comparison of the (top) fast electric field change and (bottom) consecutive high-speed video frames of a sequence of recoil leaders visible below cloud base.

exceptions are the reports by *Rhodes et al.* [1994] and *Mazur et al.* [1995], who analyzed data from a VHF radio interferometer. *Rhodes et al.* [1994] discusses in detail the development of the initial leader of a cloud-to-ground flash with the help of electric field waveforms and VHF radiation source locations. They mention that "several fast streamers occurred during the initial leader," among which three of them are shown in the radiation source location plots [*Rhodes et al.*, 1994, p. 13,070 and Figure 9b]. Rhodes et al. further describe that each streamer "began beyond the starting point of the leader and progressed rapidly into the start region along one of two branches that were established during the preceding intracloud activity" and that they "occurred mostly during the first half of the leader" development [*Rhodes et al.*, 1994, p. 13,070 and Figure 9c]. *Mazur et al.* [1995] observed a similar behavior in the VHF emitted by a dart leader that became a stepped leader that preceded the third stroke of a six-stroke flash. This event was also recorded on a high-speed camera (1000 frames per second), and the authors note that the channel of the third stroke "brightened substantially 3 ms before reaching ground (frame 233, Figure 7)," even though "the luminosity decreased in the next frame and did not increase again until the return stroke" [*Mazur et al.*, 1995, p. 25,736 and Figure 7]. Mazur et al. also state that "the leader brightening was preceded in the interferometer observations by a fast in-cloud streamer that propagated into the upper end of the leader channel (event a, Figures 6a–6c)" [*Mazur et al.*, 1995, p. 25,736 and Figure 6]. They also highlight the similarity of the "fast in-cloud streamer" to those reported by *Shao* [1993] and *Rhodes et al.* [1994] during leader development. We believe that both of the above reports are similar to the type β_2 leader observations made by *Schonland et al.* [1938] except that the event described by *Mazur et al.* [1995] began its development as a dart leader, later becoming a stepped leader.

The "fast streamers" of *Rhodes et al.* [1994] and the "M-type event" of *Mazur et al.* [1995, p. 25,731] seem to match the description of the *dart streamer* by *Schonland et al.* [1938]; i.e., they seem to catch up with the tip of a stepped leader during the final stage. While neither of the above works give any estimates of speed that can be compared to the minimum value calculated by *Schonland et al.* [1938, p. 461], *Shao et al.* [1995, Figure 26] presented histograms of the speeds of dart leaders, attempted leaders, K events, and recoil events measured through the same VHF interferometry technique. With only one exception, they were all faster than the minimum speed (2.0×10^6 m s^{-1}) estimated by *Schonland et al.* [1938].

More recently, *Lu et al.* [2008, pp. 71–72 and Figure 3] have obtained high-speed video recordings of an "attempted leader" that could be a "dart streamer" of a type β_2 dart-stepped leader. The leader presented a maximum speed of 1.1×10^6 m s^{-1}, which is comparable to the minimum speed of 2.0×10^6 ms^{-1} in flash 102 reported by *Schonland et al.* [1938, p. 461]. *Lu et al.* [2008, p. 72] state that a return stroke (fourth in a 13-stroke flash) was produced 3.6 ms after the attempted leader occurred and hypothesize two possible explanations for that event: (i) it continued developing with a speed of 2.7×10^5 m s^{-1} (typical of a stepped leader) over the bottom 800 m of the channel with a brightness that was below camera sensitivity or (ii) it was a regular attempted leader that was followed by a dart leader with a speed higher than 1.0×10^7 m s^{-1}. If (i) is true, that event was probably a dart leader that became a stepped leader of β_2 type, with the attempted leader being its single dart streamer. *Lu et al.* [2008] however state that (ii) was more likely to be true, even though it is not explicitly said whether this return stroke followed the exact same channel to ground as any of the three preceding strokes.

Based on electric field measurements and an extensive literature review, *Beasley et al.* [1982, p. 4901] argue that "the historical use of such terms as "type α" and "type β" could be viewed as identifying extremes in the range of variability of the discharge processes rather than completely different physical processes," adding that they "feel it prudent to discontinue use of the designations in order to emphasize the point of view that there is only one stepped leader process." *Campos et al.* [2014] have analyzed how downward leader speeds change with height, and they do not give any evidence in favor of such categorizations, even though 9% of their stepped leaders decelerated and could well fit a type β classification. Nine percent is a very low percentage compared to what was reported by *Schonland* [1938, 1956], and *Campos et al.* [2014] found no other indications that it is necessary to create other categories. *Campos and Saba* [2013] presented a detailed case study of a stepped leader event, whose early, bright development became visible above cloud base and progressed simultaneously with the production of initial breakdown pulses. Visually, it fits the historical definition of a type β leader, but the temporally correlated electric field records suggest that it did not differ significantly from regular stepped leaders. Other studies however have maintained the historical terminology, and it is not even clear if those authors view types α and β as distinct physical processes [*Lu et al.*, 2008; *Nag and Rakov*, 2009]; so the question remains open. Even though we agree with *Beasley et al.* [1982], we will keep the type β_2 nomenclature here not only for historical reasons but also in an attempt to differentiate a β_2 process from the "regular" and most common stepped leader where dart streamers are not observed.

Kasemir [1950, 1960] introduced the concept of a bidirectional, bipolar, and zero-net-charge leader to describe the initiation and development of lightning flashes. This concept has been summarized by *Kawasaki et al.* [2002, p. 56], who describe it by saying that "a lightning discharge is initiated with both positive and negative leaders progression simultaneously in opposite directions from its origin." Some evidence in favor of this view has been obtained in experiments involving aircraft-triggered lightning, with their results and interpretation presented by *Mazur* [1989] and in UHF interferometer experiments on upward initiated lightning in Japan conducted by *Kawasaki et al.* [2002] and *Kawasaki and Mazur* [1992]. Within the framework of a bidirectional leader concept, the role of processes previously known as *K* changes, or recoil streamers, has been revisited. They were renamed *recoil leaders* (RLs) by *Mazur* [2002, p. 1394], and the present interpretation is that RLs are "self-propagating discharges, moving along previously developed trails of the positively charged parts of bidirectional and zero-net-charge leaders." This idea serves as the framework for a more global view of lightning breakdown in which recoil processes are waves of negative breakdown that propagate in a retrograde fashion along previously formed positive channels. Negative dart leaders can be viewed simply as RLs that reach ground after the channel current has been cut off [*Shao et al.*, 1995; *Mazur*, 2002]. *M* components could be RLs that are initiated within the branches of a positive leader that is producing the continuing current following a CG stroke, etc. [*Mazur and Ruhnke*, 2011; *Campos and Saba*, 2012].

Early studies by *Brook and Ogawa* [1977] used electric field changes to estimate the speed of propagation of *K* changes in intracloud lightning, and they obtained an average speeds of 1.3×10^6 m s^{-1}. Later, *Richard et al.* [1986] and others have examined the propagation of VHF-UHF radiation sources during intracloud flashes and found that they moved over distances of a few to more than 10 km at speeds on the order of 10^7 m s^{-1}. More recently, *Saba et al.* [2008] have analyzed high-speed video recordings of RLs during +CG flashes and have found that they are produced up to 120 ms before the return stroke and also afterward during the continuing current. These authors also note that the RLs develop in a retrograde fashion, i.e., propagate toward the leader origin [*Saba et al.*, 2008, Figures 4d, 4e, and 4f] at a minimum speed of 4×10^6 m s^{-1}. All the above speed estimates are in fair agreement with what is observed not only for the dart leaders in negative CG flashes [e.g., *Schonland et al.*, 1935; *Orville and Idone*, 1982; *Jordan et al.*, 1992; *Mach and Rust*, 1997; *Campos et al.*, 2014] but also in the one dart streamer in a type β_2 negative leader, whose speed could be estimated by *Schonland et al.* [1938]. *Warner* [2012] has observed recoil activity in the branches of upward propagating, positive leaders whose initiation is induced in response to negative cloud charge transferred to ground by positive cloud-to-ground flashes in the vicinity of tall towers. No RL speed estimates were made by *Warner* [2012]. From the analysis of the same class of phenomenon, *Mazur et al.* [2013] have found optical evidences that RLs are in fact bipolar discharges that develop bidirectionally. In their high-speed video observations, it is possible to notice that the early RL development occurs in two directions, with the final stages only propagating toward the branching point of the conducting upward leader channel [*Mazur et al.*, 2013, Figure 4]. And finally, *Saraiva et al.* [2014] presented two detailed case studies of cloud-to-ground bipolar flashes whose subsequent negative strokes were clearly initiated by RLs that were visible below cloud base. This result can be extended to subsequent strokes of regular negative CG flashes, in agreement with the bidirectional leader concept and interpretation.

In an attempt to describe the type β_2 leader in a general framework of lightning breakdown, i.e., within a bidirectional, zero-net-charge leader model, we suggest that the luminous processes that are termed dart streamers by *Schonland et al.* [1938] are actually the visible manifestation of recoil leaders that began in previously ionized branches of the upper positive portion of a bipolar leader system. Some of the RLs connect to branches that are still active, propagate through the developing leader channels, and reach the lower negative portion of the stepped leader while it is still moving toward ground, becoming visible below cloud base.

In the following, we will describe seven examples of negative type β_2 leader events that were recorded on a digital high-speed camera, and then we will describe our hypothesis in greater detail. Three of the seven events also had correlated electric field waveforms that will also be described in detail.

2. Instrumentation

The data presented here were obtained using a single, high-speed digital camera (all seven events) and a fast electric field sensor (in three cases) during two field campaigns aiming to study the characteristics of negative CG flashes. Four cases were observed during a campaign conducted in Tucson, Arizona, during July–August 2007, and that data set has been described by *Saraiva et al.* [2010]. The three negative flashes with correlated electric field measurements were recorded in São José dos Campos, São Paulo, Brazil, during February 2011. Similar studies of positive CG flashes on both locations and based on the same instruments have been described by *Saba et al.* [2008, 2009, 2010].

2.1. High-Speed Camera

The high-speed digital camera (Photron FASTCAM 512 PCI) was operated at a sample rate of 4000 frames per second or a 250 μs exposure time per frame. The video frames were GPS time stamped, and there was no frame-to-frame persistence of luminosity. By making a detailed comparison of the video data with the fast electric field records obtained during six return strokes (recorded at either 4000 or 8000 frames per second), it has been verified that the time stamps were made at the beginning of a given video frame. Such analyses were necessary in order to derive the results described in section 3 of this paper.

Data acquisition from the video camera was initiated using a signal derived from an external source and, for the present study, this signal came from a button pressed by the camera operator. The total recording time was 2 s, and the pre-trigger and post-trigger times within that interval were each 1 s. One second proved to be long enough to prevent the initial stroke from being missed and also to allow the complete flash to be recorded [*Saraiva et al.*, 2010]. The accuracy of high-speed cameras for measuring lightning parameters has been discussed by *Ballarotti et al.* [2005], *Saba et al.* [2006, 2008], and *Campos et al.* [2007, 2009]. One recurring issue in those studies has been how to answer the question of which parameters can be determined for processes whose occurrence and duration are shorter than the exposure time of an individual frame. In such cases, all that can be determined is the maximum duration and occurrence-related parameters [*Campos et al.*, 2007, 2009; *Campos and Saba*, 2009] or a minimum (2-D) propagation speed [*Saba et al.*, 2008; *Campos et al.*, 2014]. The latter limitation also applies to some of the "luminous processes" that were observed during the development of the β_2 leaders that are described here.

For the analysis of each event, the algorithm developed by *Campos et al.* [2007, 2009] was used to obtain luminosity-*versus*-time curves. It is responsible for calculating the average pixel value per frame for a user-selected area, making it possible to estimate the variations in channel luminosity as time advances.

2.2. Fast Electric Field Sensor

For the three events recorded in São José dos Campos, three flat plate antennas were operated in order to measure the electric field changes produced by lightning. Two of these antennas operated in a fast mode, i.e., using an integrator/amplifier with a bandwidth that went from 306 Hz to 1.5 MHz and a decay time constant of approximately 500 μs. A GPS receiver provided time synchronization, and the data acquisition system contained a 12-bit analog to digital converter operating at a sampling rate of 5 MS/s on each of three channels. In order to guarantee enough sensitivity and not have saturation, two antennas were operated simultaneously using sensitivities that differed by a factor of 10. A third antenna was connected to the same data acquisition system (GPS and analog to digital converter), but its integrator/amplifier circuit was configured to have a 1.5 s decay time so it acted as a "slow" field change sensor.

2.3. Lightning Locating System

For estimating channel length and two-dimensional (2-D) propagation speed, it is necessary to know the geometry of the camera and lens and the distance from the observation site to the lightning event. The latter parameter, the stroke polarity, and an estimate of the peak current were obtained from reports of the National Lightning Detection Network (NLDN) in Arizona and from the Brazilian Lightning Detection Network (BrasilDAT) in São Paulo. The time matching between the camera and the lightning locating systems (LLS) was done by GPS time synchronization [*Ballarotti et al.*, 2005]. Both observation sites were located in regions that were well covered by their respective LLS [*Cummins and Murphy*, 2009; *Naccarato and Pinto*, 2009].

3. Observations and Data

In section 3.1, we describe two recoil leader events in order to gain an understanding of how the electric field waveforms are related to the optical properties of RLs [see also *Saba et al.*, 2008]. Subsequently, on section 3.2, we describe β_2 leader events observed in the development of seven lightning flashes. And finally, in section 4, the descriptions of both sections 3.1 and 3.2 are used to discuss the physical characteristics of the type β_2 leaders and some inferences that are made regarding their nature.

When describing each case, the time interval over which the leader propagates as a regular (type α) stepped leader or dart leader will be referred as the stepped leader phase or dart leader phase, respectively. Even though we will preserve the historical terminology for type β_2 leaders, we will refer to the *dart streamers*, first described by *Schonland et al.* [1938], simply as *luminous processes* (or LPs). Also, in order to maintain a uniform terminology for measuring the 2-D speeds of each leader, we will use the definitions given by *Saba et al.* [2008, p. 2]; i.e., *partial speeds* are the "speeds measured along the path of the leader," while the *average speed* "is calculated by dividing the length of the entire 2-D trajectory by the time taken to cover it." Finally, in some of the case studies, it is mentioned in the text (or in the related tables) that a *minimum speed* is provided. This means that only a lower bound of the speed of that process could be estimated. In these measurements, either the starting point of that channel increment was not visible (i.e., was located within the cloud opaque region) or its final point was reached before the end of the frame exposure (e.g., the final speed estimate right before the return stroke). In these events, we have assumed that the estimated length was traversed by the leader or luminous process over a full 250 μs interval when, in fact, the time taken was shorter (but impossible to determine).

Table 1 summarizes the characteristics of all the seven β_2 events we have recorded in our field campaigns.

3.1. Electric Field Waveforms Associated With Optical Recoil Leaders

As stated previously, we have obtained electric field records during RLs that were correlated with high-speed video measurements. On 11 February 2011 at 22:25:30 universal time (UT), two strokes were recorded on video (one positive, with an estimated peak current of +73 kA, and another that was not detected by BrasilDAT). In the time interval between these strokes, several recoil leaders were recorded on video, which made it possible to compare their times of occurrence with the fast electric field records, as shown in Figure 1. Here the time axis of the E-field waveform has been divided into equal parts in order clarify which interval corresponds to each video frame. It should be noted that the occurrence of each (visible) recoil is associated with the production of short duration burst of electric field pulses (microsecond scale) that are well above the noise level. No propagation direction or speed could be estimated for any of these events because a portion of their development occurred outside the field of view of the camera. Given our limited video

Table 1. Summary of the Characteristics of Seven β_2 Events[a]

Case Number	Location	Stroke Order	Distance (km)	I_p (kA)	Average Leader 2-D Speed (10^5 m s^{-1})	Number of LPs	Average LP 2-D Speed (10^5 m s^{-1})
1	TUS	1	12.3	−13	3.47	2	*104*
2	TUS	1	31.5*	NA	0.46	4	38.3
3	TUS	2 (NC)	29.6	−14.5	1.53	2	106
4	TUS	2 (SC)	12.3*	NA	10.8	1	94.9
5	SJC	2 (NC)	14.6*	NA	2.37	2	114
6	SJC	1	5.90	−12.0	1.99	1	*45.3*
7	SJC	5 (NC)	17.5*	NA	1.84	3	*91.7*

[a]TUS stands for Tucson, SJC for São José dos Campos, NA for not available, SC for same channel, NC for new channel, I_p for estimated peak current, and LP for "luminous process." The cases that have distances marked with an asterisk were strokes that were not reported by a LLS but had locations that could be estimated from other strokes in the same flash that remained in the same channel and were reported. In cases 1, 6, and 7, only the minimum speeds of the LPs could be calculated (indicated in italic).

sampling rate and field of view, it is not possible to know whether two or more individual pulses are related to a single recoil event. The shape of the slow (millisecond-scale) field changes on which the bursts of microsecond pulses are superimposed indicates that they were produced by a negative recoil leader.

3.1.1. Case 1: First Stroke in an Eight-Stroke Flash

Case 1 occurred at 20:37:53 UT on 25 July 2007 in Tucson. This flash produced eight strokes, and all remained in the same channel to ground. The first stroke had an NLDN estimated peak current, $I_p = -13$ kA, and its location was 12.3 km from the camera. This stroke was initiated by a type β_2 stepped leader. The eighth stroke in the flash was reported by the NLDN and had an $I_p = -8.4$ kA and was located 13.6 km from the camera.

The video frames showed that there were two luminous processes, and after the first, there was an abrupt decrease in the speed of the stepped leader. After the second one, however, there was no change in speed that could be measured with the time resolution of the camera. Data suggests that there were no pauses in the progression of the stepped leader either before or after the LP occurred. If it has occurred, it was not longer than 500 μs (which is the shortest pause duration that could be detected with the available framing rate). In contrast, the β_2 event in flash 92 of *Schonland et al.* [1938] presented a pause of 9 ms before the LP was observed. Figure 2 also shows the sequence of consecutive video frames that correspond to each phase of Case 1. Figure 3 shows the time variation of leader speed and luminosity as it propagated toward the ground (the same data are given in greater detail in Table 2). The luminosity-*versus*-time graph was computed using an algorithm that is described in detail by *Campos et al.* [2007, 2009].

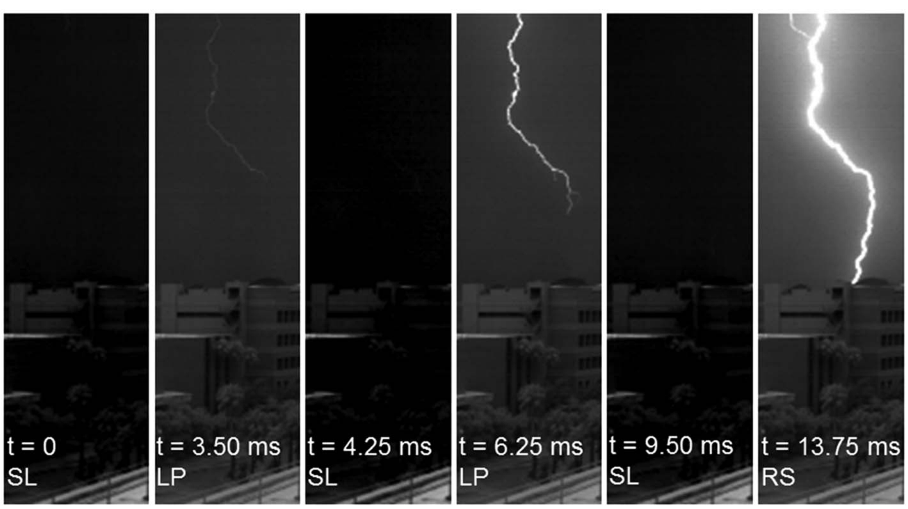

Figure 2. Selection of sectioned video frames that shows Case 1. SL stands for the stepped leader phase of a type β_2 leader, LP indicates a luminous process, and RS is the return stroke. The contrast has been modified in the SL frames to enhance a very faint leader tip.

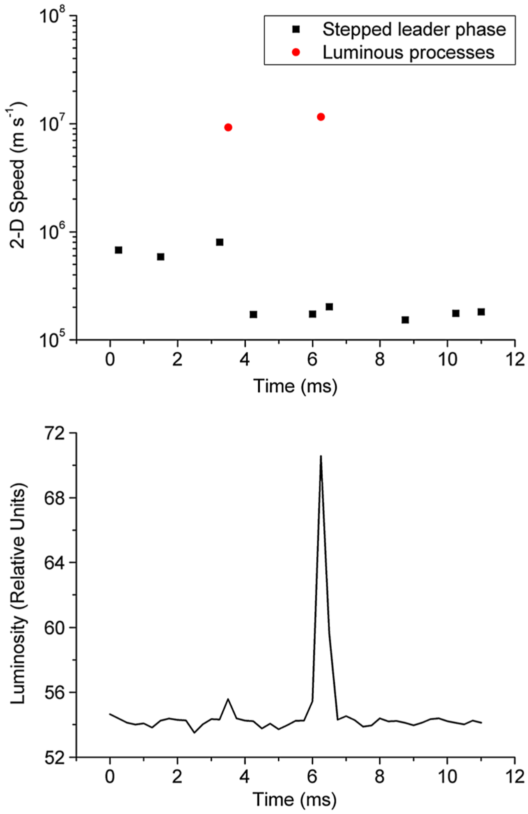

Figure 3. Temporal evolution of the (top) 2-D leader partial speed and (bottom) luminosity computed during the β_2 leader in Case 1. Time $t = 0$ corresponds to the frame in which the leader first became visible in the camera field-of-view, and the return stroke occurred at $t = 13.75$ ms. SL stands for the stepped leader phase and LP for luminous process. The first LP ($t = 3.50$ ms) could have only its minimum speed estimated.

3.1.2. Case 2: First Stroke in a Three-Stroke Flash

Case 2 occurred at 02:46:06 UT on 16 August 2007 in Tucson. The flash contained three strokes, and all remained in the same channel. The first stroke was initiated by a type β_2 leader, and only the third stroke was detected by the NLDN ($I_p = -8.5$ kA, $D = 31.5$ km). The estimated distance to the third stroke was used to calculate the speed of the leader preceding the first stroke.

The channel luminosity of the stepped leader phases of Case 2 was too faint to be recorded, even with the help of contrast enhancement on the camera, but the four luminous processes were very intense; this has enabled the extreme points reached by the leader tips to be estimated during the time between LPs. As this leader preceded the first stroke of the flash (which strongly suggests that it is of stepped nature) and by assuming that each LP interrupts its development when it reaches the current leader tip, the 2-D speeds of the stepped leader phases were calculated by dividing the difference in the channel length from the occurrence of one LP to the next by the time interval between them. The last speed estimate was obtained in a similar way, but this time taking the time difference between the fourth LP and the instant of the return stroke. Considering these limitations, it was difficult to determine how the propagation speed changed within the stepped leader phase after each LP occurred, but there does appear to be a reduction in speed after the second one and an apparent increase after the third and fourth ones. All LPs were visible for at least two frames, allowing their 2-D speeds to be estimated. Table 3 gives a detailed description of each phase of Case 2, correlating time, height, and speed.

3.1.3. Case 3: Second Stroke (New Channel) in a Five-Stroke Flash

Case 3 was the second stroke in a five-stroke negative flash that occurred at 03:17:42 UT on 16 August 2007 in Tucson. This stroke produced a different ground termination than the first stroke and was preceded by a type β_2 stepped leader. All return strokes after the second (from third to fifth) remained in the same channel as the second. About 33.5 ms after the first stroke, there was an "attempted dart

Table 2. Average 2-D Speeds (for Each Phase) and Heights of the Leader Tip for Case 1[a]

Relative Time (ms)	Δt (ms)	Phase Type	Upper End Height (m)	Midpoint Height (m)	Lower End Height (m)	Vertical Increment (m)	Horizontal Increment (m)	2-D Channel Increment (m)	Partial 2-D Speed ($\times 10^5$ m s^{-1})
0–3.25	3.25	SL	3660	2680	1690	1970	1210	2310	7.10
3.25–3.50	0.25	LP (1)	3660	2680	1690	1970	1210	2310	92.3 (*min*)
3.50–6.00	2.50	SL	1690	1480	1260	430	46	430	1.72
6.00–6.25	0.25	LP (2)	2470	1870	1260	1210	1370	1830	73.0
6.25–11.00	4.75	SL	1210	860	500	710	350	790	1.67
13.75	*2.75*					*Return stroke*			

[a]Time $t = 0$ was taken at the GPS time of the first video frame in which the leader tip became visible. SL stands for the stepped leader phase and LP for a luminous process. Only the minimum speed could be estimated for the first LP. All length estimates were rounded toward infinity with a 10 m resolution after the speeds were calculated.

Table 3. Average 2-D Speeds (for Each Phase) and Ranges of the Leader Tip Height for Case 2[a]

Relative Time (ms)	Δt (ms)	Phase Type	Upper End Height (m)	Midpoint Height (m)	Lower End Height (m)	Vertical Increment (m)	Horizontal Increment (m)	2-D Channel Increment (m)	Partial 2-D Speed ($\times 10^5$ m s^{-1})
0–0.25	0.25	LP (1)	2200	1970	1740	450	65	460	18.3
0.50–17.75	17.25	SL	1740	1550	1360	390	580	700	0.41
17.75–18.00	0.25	LP (2)	2200	1780	1360	840	650	1060	42.4
18.00–32.50	14.50	SL	1360	1200	1030	320	0	320	0.22
32.50–32.75	0.25	LP (3)	1870	1450	1030	840	260	880	35.1
33.00–51.25	18.25	SL	1030	780	520	510	80	520	0.29
51.25–51.50	0.25	LP (4a)	2580	1710	840	1740	900	1960	78.5
51.50–51.75	0.25	LP (4b)	840	650	450	390	190	430	17.3
52.00–54.25	2.25	SL	520	420	320	200	120	230	1.03
54.75	*0.50*					*Return stroke*			

[a]Time $t = 0$ was taken at the GPS time of the video frame in which the first luminous process was observed. SL stands for stepped leader phase and LP for luminous process. The fourth LP could be clearly observed on three frames, which permitted two estimates of partial speeds (4a and 4b). All length estimates were rounded toward infinity with a 10 m resolution after the speeds were calculated.

leader" down the original channel, and after 227 ms, there was a second stroke that produced a new ground termination and was preceded by a type β_2 leader. The first ($I_p = -17$ kA, $D = 29.9$ km), second ($I_p = -14.5$ kA, $D = 29.6$ km), and fourth ($I_p = -13.6$ kA, $D = 28.5$ km) return strokes were detected by the NLDN. Given the long time interval between the attempted dart leader and the second stroke (of approximately 193.5 ms), we do not think the attempted leader was related to the type β_2 leader that initiated the second stroke.

The initial first stepped leader phase leading to the second return stroke was too faint to be recorded on the high-speed video camera, so it was necessary to use the same technique (under the same assumptions) that was described previously for Case 2 to estimate speed values. It was also difficult to determine if there was a change in the stepped leader speed after each luminous process, but the speed does appear to increase after the second LP. Table 4 details all phases of this leader and shows how the height of the leader tip and speed changed with time.

3.1.4. Case 4: Second Stroke (Partially New Channel) in a Three-Stroke Flash

Case 4 occurred at 03:49:40 UT on 16 August 2007 in Tucson. It produced three strokes, with the second and third ones producing a different ground strike point from the first. The first stroke was reported by the NLDN ($I_p = -13$ kA, $D = 12.3$ km). As shown in Figure 4 and Table 5, the second stroke began with a very bright dart leader that progressively becomes darker and slower over the first 2.50 ms after it first became visible. Over that period, it decelerated from 2.23×10^6 m s^{-1} to 4.27×10^5 m s^{-1}, and by that time, its channel tip was about 600 m above ground. A very fast (9.49×10^6 m s^{-1}) luminous process then occurs, brightening the channel and reaching its lower tip. One frame after the occurrence of the LP, it is possible to see some branching forming, indicating the transition from the dart leader to the stepped leader phase, with the β_2 leader traversing the final 400 m to ground with a speed of approximately 2.16×10^5 m s^{-1}. After the branching point (which was located about 700 m above ground), the leader followed a new channel to ground, producing a different strike point from the first stroke. The third and last stroke followed the same channel as the second.

Table 4. Average 2-D Speeds (for Each Phase) and Range of Leader Tip Height for Case 3[a]

Relative Time (ms)	Δt (ms)	Phase Type	Upper End Height (m)	Midpoint Height (m)	Lower End Height (m)	Vertical Increment (m)	Horizontal Increment (m)	2-D Channel Increment (m)	Partial 2-D Speed ($\times 10^5$ m s^{-1})
0–0.25	0.25	LP (1)	2370	2160	1940	430	420	600	23.9
0.50–7.75	7.25	SL	1940	1430	910	1030	180	1050	1.44
7.75–8.00	0.25	LP (2)	2730	1820	910	1820	960	2060	82.2
8.75–12.00	3.25	SL	790	520	240	550	0	550	1.68
12.75	*0.75*					*Return stroke*			

[a]Time $t = 0$ was taken at the GPS time of the video frame in which the first luminous process became visible. SL stands for a stepped leader phase and LP for a luminous process. All length estimates were rounded toward infinity with a 10 m resolution after the speeds were calculated.

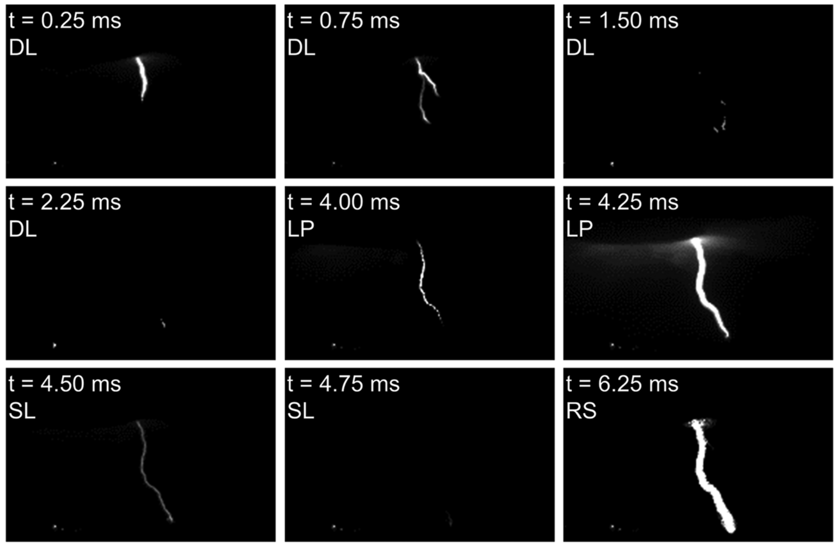

Figure 4. Selection of sectioned video frames recorded for Case 4. DL stands for the early dart leader phase of the type β_2 leader, SL stands for its stepped leader phase, LP indicates a luminous process, and RS is the return stroke. The contrast has been enhanced in the frames that correspond to $t = 1.50$ ms and $t = 2.25$ ms in order to provide a better visualization. Branching can be seen to form at $t = 4.50$ ms, right after the luminous process, marking it transition to the stepped leader phase and causing the β_2 leader to produce a new ground termination.

3.1.5. Case 5: Second Stroke (New Channel) in a Three-Stroke Flash

Case 5 occurred at 18:01:45 UT on 02 February 2011 in São José dos Campos. This was a three-stroke flash, and the second stroke created a new ground termination that was initiated by a type β_2 stepped leader. The third stroke was about 33.75 ms after the second, remained in the same channel as the second stroke, and was detected by BrasilDAT ($I_p = -12.0$ kA, $D = 14.6$ km).

The second stroke of Case 5 begins about 13 ms after the first and develops in the form of a dart leader propagating toward ground in a branch that formed during the development of the stepped leader that preceded the first stroke. Figure 5 and Table 6 show the results of computing the leader tip height, two-dimensional partial speed, channel luminosity, and the associated fast electric field change. The leader tip height values of the topmost plot of Figure 5 correspond to the height of the midpoint between the two leader positions used on each partial leader speed measurement. It can be seen in Table 6 that the leader speeds were in the 10^6 m s^{-1} range until the tip was about 1500 m above the ground, and then it began to propagate through virgin air. The speed drops at this time to the 10^5 m s^{-1} range. About 2 ms after the stepped leader phase began, the first LP propagated toward the leader tip, and the second LP was initiated 4 ms later. Even though the data from the slow electric field sensor were available, they are not presented here because they show only a slow and steady change in the overall leader propagation.

Table 5. The 2-D Partial Speeds and the Ranges of Leader Tip Height for Case 4[a]

Relative Time (ms)	Δt (ms)	Phase Type	Upper End Height (m)	Midpoint Height (m)	Lower End Height (m)	Vertical Increment (m)	Horizontal Increment (m)	2-D Channel Increment (m)	Partial 2-D Speed ($\times 10^5$ m s^{-1})
0–0.25	0.25	DL	2550	2270	1990	560	0	560	22.3
0.25–0.50	0.25	DL	1990	1710	1430	560	70	560	22.5
0.50–0.75	0.25	DL	1430	1350	1270	160	160	220	9.00
0.75–1.75	1.00	DL	1270	1070	870	400	280	490	4.85
1.75–2.50	0.75	DL	870	740	600	270	170	320	4.27
3.75–4.00	0.25	LP	3060	1890	720	2340	360	2370	94.9
4.25–6.00	1.75	SL	400	220	40	360	120	380	2.16
6.25	*0.25*					*Return stroke*			

[a]Time $t = 0$ was taken as the GPS time of the frame in which the tip of the dart leader phase was first observed. DL stands for dart leader phase, SL for stepped leader phase, and LP for luminous process. All length estimates were rounded toward infinity with a 10 m resolution after the speeds were calculated.

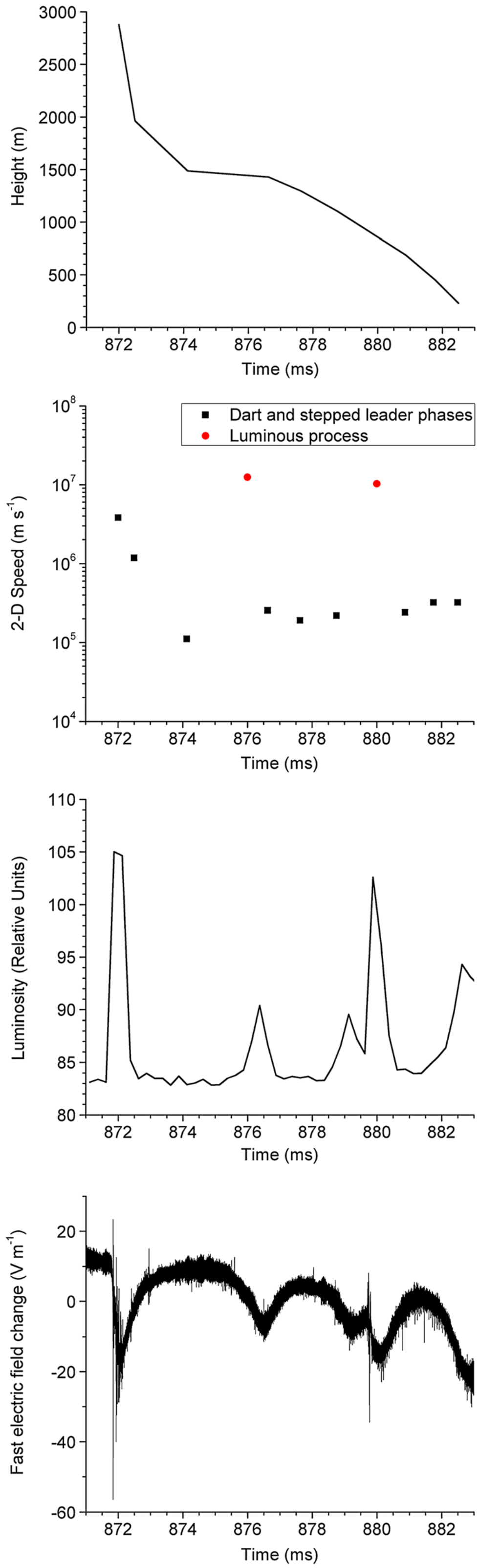

Figure 5. Time-correlated height of the leader tip, 2-D partial speeds, channel luminosity, and the fast electric field change for Case 5. The return stroke occurs at time $t = 883.700$ ms (not shown).

A detailed comparison between high-speed video records (sectioned frames) and the fast electric field data during the second LP of Case 5 is given in Figure 6. As mentioned in section 2.1, the time stamp in each video frame occurs at its beginning. During frame c, i.e., between times $t = 879.500$ ms and 879.750 ms (taking time $t = 0$ at the beginning of the second in which the whole leader process occurred as provided by the GPS synchronization), there is a sequence of pulses that continues until the beginning of frame d, in which the first part of the propagation of the LP becomes visible below cloud base. The electric field signal returns to noise level at approximately $t = 879.810$ ms, and the LP finishes its propagation on frame e and returns to the original luminosity level between frames f and g. From analyses such as this, we infer that the electric field pulses occur prior to the development of the LP and its propagation toward the leader tip below the cloud base. This, in turn, suggests that the E pulses are caused by processes inside the cloud and are not directly related to the LP propagation. The two higher-amplitude pulses that occur at the beginning of frame d had durations of approximately 3.2 and 6.2 μs. A similar analysis was made for the first LP (that occurred between times $t = 875.750$ ms and $t = 876.250$ ms), and the same temporal relationship between the occurrence of E pulses and LP development was found. In section 3.3, we will see that the association of electric field pulse activity with the genesis of a luminous process is similar to pulses during *M* components and *K* changes [e.g., *Krider et al.*, 1975; *Bils et al.*, 1988; *Thottappillil et al.*, 1990; *Rakov et al.*, 1992; *Campos and Saba*, 2012] and also to visible recoil leaders (as discussed in section 3.1 and shown in Figure 1).

3.1.6. Case 6: Forked Stroke

Case 6 occurred at 18:44:10 UT on 13 February 2011 in São José dos Campos and was a forked or double-grounded stroke initiated by a type β_2 stepped leader. The forked portion of the channel that was closer to the camera was the first to contact ground (at approximately $t = 484.115$ ms, if time $t = 0$ is taken at the beginning of the second in which the whole leader process occurred as provided by the GPS synchronization) and was the only one reported by BrasilDAT ($I_p = -12.0$ kA, $D = 5.90$ km). The more distant channel contacted ground at approximately $t = 484.265$ ms and appeared one frame after the first on the video record.

Figure 7 gives results of time-correlated analyses of the leader tip height, two-dimensional leader speed, channel luminosity, and fast electric field change for Case 6, and Table 7 gives numerical values of all partial speed measurements provided by the high-speed cameras (in 2-D). The leader tip height values of the topmost plot of Figure 7 correspond to the height of the

Table 6. The 2-D Partial Speeds and the Ranges of Leader Tip Height for Case 5[a]

Time (ms)	Relative Time (ms)	Δt (ms)	Phase Type	Upper End Height (m)	Midpoint Height (m)	Lower End Height (m)	Vertical Increment (m)	Horizontal Increment (m)	2-D Channel Increment (m)	Partial 2-D Speed ($\times 10^5$ m s^{-1})
872.00–872.25	0–0.25	0.25	DL	3350	2880	2400	950	0	950	38.1
872.25–873.00	0.25–1.00	0.75	DL	2400	1960	1520	880	150	890	11.9
873.00–875.50	1.00–3.50	2.50	SL	1520	1490	1450	70	270	280	1.11
876.00–876.25	4.00–4.25	0.25	LP (1)	4500	3000	1490	3010	770	3110	124
876.25–877.25	4.25–5.25	1.00	SL	1490	1430	1370	120	230	260	2.56
877.25–878.25	5.25–6.25	1.00	SL	1370	1300	1220	150	110	190	1.91
878.25–879.50	1.25–7.50	1.25	SL	1220	1110	990	230	150	270	2.20
880.00–880.25	8.00–8.25	0.25	LP (2)	2940	1930	910	2030	1590	2580	103
880.50–881.50	8.50–9.50	1.00	SL	800	690	570	230	80	240	2.41
881.50–882.25	9.50–10.25	0.75	SL	570	460	340	230	80	240	3.21
882.25–883.00	10.25–11.00	0.75	SL	340	230	110	230	80	240	3.21
883.50	*11.50*	*0.50*					*Return stroke*			

[a]Time $t = 0$ was taken at the beginning of the GPS second in which the leader process began. The leader tip was first visible at $t = 871.750$ ms, and the return stroke occurred at $t = 883.500$ ms. DL stands for dart leader phase, SL for stepped leader phase, and LP for luminous process. All length estimates were rounded toward infinity with a 10 m resolution after the speeds were calculated.

midpoint between the two leader positions used on each partial leader speed measurement. A luminous process occurs in both branches of the forked channel between $t = 479.750$ ms and $t = 480.000$ ms. As in Case 5, the slow electric field exhibited only a slow and uniform behavior during the LPs; therefore, it is not presented here. A detailed comparison of the high-speed video data (sectioned frames) with the fast electric field is given in Figure 8. Similar to Case 5 (Figure 6), the sequence of frames c, d, and e show that electric field pulses precede the development of the LP toward the lower leader tip below cloud base. Because of this and the fact that the LP was simultaneous on both sections of the fork (at least within the time resolution of the camera), we believe that the LP in both sections shared a common genesis inside the cloud. Six individual E pulses that occurred between $t = 484.500$ ms and $t = 484.850$ ms, i.e., during frames c and d, could have their durations estimated, which ranged from 2.6 μs to 14.2 μs, with a mean of 6.1 μs. These values are in good agreement with the pulses that were observed during the second LP of Case 5. These characteristics also resemble the pulse activity associated with optical recoil leaders (Figure 1), as further explored in section 3.3.

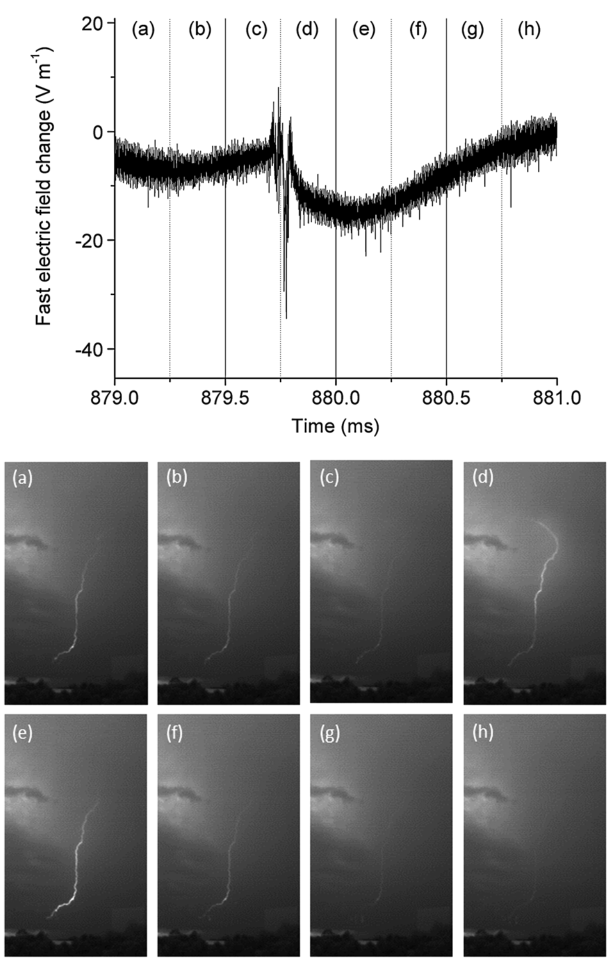

Figure 6. Detailed comparison of the (top) fast electric field change and (bottom) consecutive high-speed video frames during the second luminous process that occurred during Case 5.

3.1.7. Case 7: Fifth Stroke (New Channel) in a Nine-Stroke Flash

Case 7 has occurred at 18:18:17 UT on 15 February 2011 in São José dos Campos. This flash contained nine strokes and produced six different ground contacts. The fifth stroke was initiated by a type β_2 stepped leader and created the fifth ground

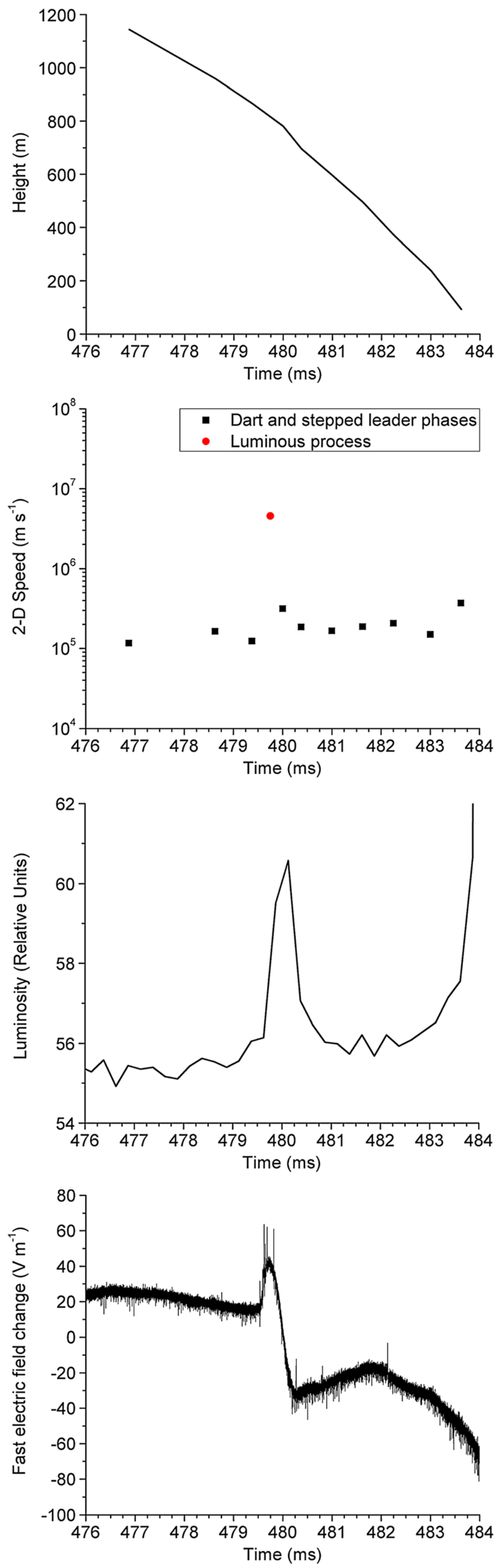

Figure 7. Time-synchronized data on the height of the leader tip, 2-D partial speed, channel luminosity, and fast electric field change for Case 6. The return stroke occurs at time $t = 484.115$ ms (not shown).

termination of this flash. The sixth stroke followed the same channel to ground as the fifth, and was reported by the BrasilDAT ($I_p = -27.0$ kA, $D = 17.5$ km), which made it possible to estimate the propagation speed of the β_2 leader before the fifth stroke. The seventh stroke created a sixth ground termination, was also reported ($I_p = -16.0$ kA, $D = 23.6$ km), and was followed by two additional strokes in the same channel. The ninth stroke was also reported by BrasilDAT ($I_p = -7.0$ kA, $D = 23.2$ km).

The flash in Case 7 produced three LPs during its progression toward ground, as shown in Table 8 (which details each phase of this leader and the corresponding temporal evolution of its tip height and speed). As in the two previous cases, the slow electric field sensor did not show evidence of those LPs, and the time resolution of the camera was not good enough to determine whether the pulses in the electric field preceded the first LP or were produced by it. On the other hand, when the same analysis was made for the second and third LPs of Case 7, we did observe a temporal relationship that agrees with that observed in Cases 5 and 6. We believe that the discrepancy found for the first luminous process is caused by the fact that it occurred while the leader tip was still relatively close to the inception point, so the LP was able to propagate through the channel(s) below cloud base in less than 250 μs (the temporal resolution of the camera).

3.2. General Comments, Discussion, and Summary of the β_2 Leader Observations

A simple analysis of Tables 2 through 8 shows that the stepped leader phase speeds in all seven cases were between 0.22×10^5 and 7.1×10^5 m s^{-1}, well within the range expected for "normal" stepped leaders [e.g., *Schonland*, 1956; *Berger and Vogelsanger*, 1966; *Orville and Idone*, 1982; *Thomson et al.*, 1985; *Mazur et al.*, 1995; *Shao et al.*, 1995; *Chen et al.*, 1999; *Lu et al.*, 2008; *Campos et al.*, 2014]. This is similar to what was reported by *Schonland et al.* [1938], and there is also no uniformity in the behavior of the leader during the stepped leader phase after the development of each luminous process (or *dart streamer*, as termed by Schonland et al.); i.e., some cases accelerate, others decelerate, and others do not show a change in speed. At least there is no common tendency in our data set.

Tables 2 through 8 also show that the luminous processes that occurred in the seven type β_2 leader events had speeds ranging from 1.7×10^6 to 1.4×10^7 m s^{-1}. These values are comparable to or greater than the estimated minimum speed of dart

Table 7. The 2-D Partial Speeds and the Range of the Leader Tip Heights for Case 6[a]

Time (ms)	Relative Time (ms)	Δt (ms)	Phase Type	Upper End Height (m)	Midpoint Height (m)	Lower End Height (m)	Vertical Increment (m)	Horizontal Increment (m)	2-D Channel Increment (m)	Partial 2-D Speed ($\times 10^5$ m s^{-1})
475.75–478.25	0–2.50	2.50	SL	1270	1150	1020	250	150	290	1.17
478.25–479.25	2.50–3.50	1.00	SL	1020	960	900	120	110	160	1.64
479.25–479.75	3.50–4.00	0.50	SL	900	870	840	60	0	60	1.24
479.75–480.00	4.00–4.25	0.25	LP	1700	1260	820	880	710	1130	45.3 (*min*)
480.00–480.25	4.25–4.50	0.25	SL	820	780	740	80	20	80	3.15
480.25–480.75	4.50–5.00	0.50	SL	740	700	650	90	0	90	1.86
481.00–481.50	5.00–5.75	0.75	SL	650	600	540	110	50	120	1.66
482.00–482.00	5.75–6.25	0.50	SL	540	500	450	90	20	90	1.88
482.00–482.75	6.25–7.00	0.75	SL	450	370	290	160	0	160	2.06
482.75–483.50	7.00–7.75	0.75	SL	290	240	190	110	30	110	1.50
483.50–484.00	7.75–8.25	0.50	SL	190	100	0	190	0	190	3.71
484.00	*8.25*	*0*					*Return stroke*			

[a]Time $t = 0$ was taken at the beginning of the GPS second in which the leader process began. The leader tip was first visible at $t = 475.500$ ms, and the return stroke occurred at $t = 484.000$ ms. SL stands for stepped leader phase and LP for luminous process. Only the minimum speed could be estimated "for the single observed LP". All length estimates were rounded toward infinity with a 10 m resolution after the speeds were calculated.

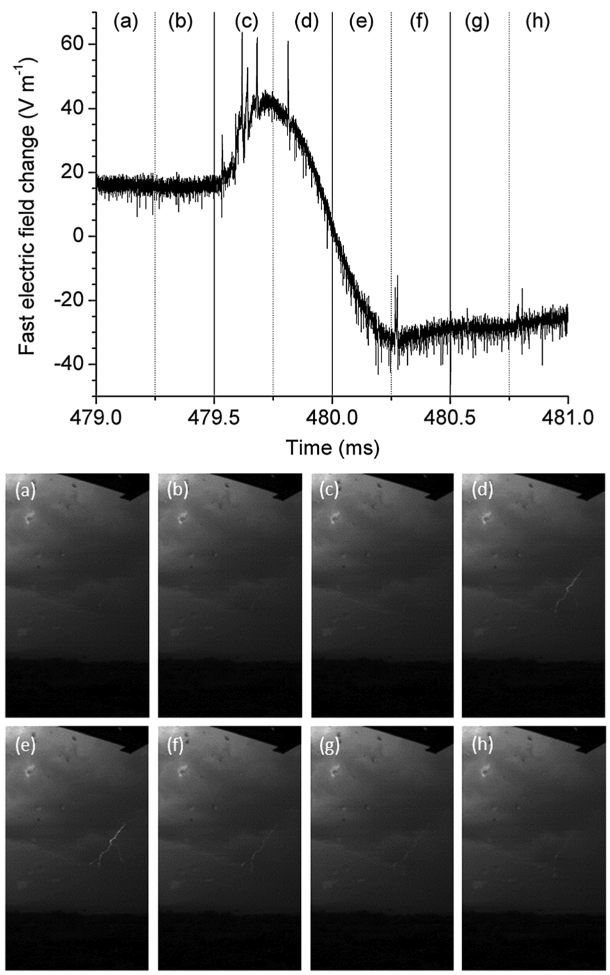

Figure 8. Detailed comparison between the (top) fast electric field change and (bottom) consecutive video frames of the single luminous process observed during the development of Case 6. Data suggests that all brightened channel branches in frames d, e, and f were affected by the same luminous process.

streamers (2.0×10^6 ms^{-1}) [*Schonland et al.*, 1938]. This range of speeds also fits into those found for typical negative dart leaders [e.g., *Schonland et al.*, 1935; *Orville and Idone*, 1982; *Jordan et al.*, 1992; *Mach and Rust*, 1997; *Campos et al.*, 2014] and recoil leaders [*Brook and Ogawa*, 1977; *Richard et al.*, 1986; *Saba et al.*, 2008]. This overall similarity supports the hypothesis that we will make in section 4.

Schonland et al. [1938, p. 463 and Table 2] found that the time intervals between dart streamers ranged from 3 to 9 ms, and this led them to suggest that their occurrence is "controlled by processes within the cloud itself." Again, Tables 2 through 8 show that the range of time intervals between subsequent luminous processes ranges from 1.75 to 18.5 ms (with a mean of approximately 9.6 ms). Only four out of the eight intervals agree with Schonland et al., but we believe that the overall results of both studies are in good agreement.

The qualitative physical description given by *Schonland et al.* [1938, p.464] that "type β_2 discharges would not be followed by many subsequent strokes" was supported by the fact that three out of the four cases they analyzed "have no subsequent strokes while the fourth, flash 92, has only one." This tendency is not supported by our data set. Case 1 was initiated by a type β_2 leader and had seven subsequent strokes; Case 2 was also initiated by a type β_2 leader and was

Table 8. Partial 2-D Speeds and Leader Tip Height Ranges for Case 7[a]

Time (ms)	Relative Time (ms)	Δt (ms)	Phase Type	Upper End Height (m)	Midpoint Height (m)	Lower End Height (m)	Vertical Increment (m)	Horizontal Increment (m)	2-D Channel Increment (m)	Partial 2-D Speed ($\times 10^5$ m s^{-1})
761.50–763.50	0–2.00	2.00	SL	3480	3420	3350	130	240	270	1.34
764.50–764.75	2.00–3.25	0.25	LP (1)	3810	3510	3210	600	1420	1540	61.7 (*min*)
764.75–766.50	3.25–5.00	1.75	SL	3160	3070	2980	180	280	330	1.89
766.75–767.00	5.25–5.50	0.25	LP (2)	3810	3370	2930	880	1650	1870	74.7 (*min*)
767.25–769.50	5.75–8.00	2.25	SL	2890	2710	2520	370	90	380	1.68
775.25–778.50	13.75–17.00	3.25	SL	1790	1540	1280	510	260	570	1.77
778.50–778.75	17.00–17.25	0.25	LP (3)	3810	2530	1240	2570	2330	3470	139 (*min*)
779.00–780.50	17.50–19.00	1.50	SL	1200	1020	830	370	0	370	2.45
780.50–781.50	19.00–20.00	1.00	SL	830	740	640	190	130	230	2.29
781.50–782.75	20.00–21.25	1.25	SL	640	550	460	180	0	180	1.47
782.75–784.50	21.25–23.00	1.75	SL	460	300	140	320	0	320	1.83
786.50	*25.00*	*2.00*					*Return stroke*			

[a]Time $t = 0$ was taken at the beginning of the second in which the whole leader process occurred provided by the GPS synchronization, with the leader tip being first visible at $t = 761.250$ ms and the return stroke occurring at $t = 786.500$ ms. SL stands for stepped leader phase and LP for luminous process. Only the minimum speed could be estimated for all three LPs. All length estimates were rounded toward infinity with a 10 m resolution after the speeds were calculated.

followed by two subsequent strokes; Case 3 occurred just before the second stroke of a five-stroke flash; i.e., it was followed by three strokes; Cases 4 and 5 occurred before the second stroke of three-stroke flashes; i.e., the leader was followed by just one stroke; the forked Case 6 had only one almost simultaneous stroke; and Case 7 was associated with the fifth stroke of a nine-stroke flash; i.e., it was followed by four strokes. Additionally, although *Schonland et al.* [1938] did not obtain return stroke peak current estimates, our data suggests that β_2 leaders do not influence the peak current of the following return strokes: only Cases 1, 3, and 6 had estimated peak currents reported by the NLDN or by the BrasilDAT, and all of those events had values that were within the range expected for negative subsequent strokes that remain in a preexisting channel (i.e., −13 kA, −14.5 kA, and −12.0 kA) [*Biagi et al.*, 2007; *Fleenor et al.*, 2009].

The electric field changes that were measured in Cases 5 through 7 show that most of the LPs that occurred in those cases were associated with electric field pulses prior to their visible development below cloud base and that they propagated toward the leader tip (see Figures 6 and 8). The first LP of Case 7 was the only exception. In that event, the electric field pulses that were not observed may have had low amplitudes because of the relatively short dimension of the channel at that moment or the pulses could have originated simultaneously with the exposure of the video frame that first showed illumination during the LP. This evidence indicates that the E pulses are caused by the genesis of LPs inside the cloud and not by their later development below cloud base.

We have also presented a brief analysis of the optical recoil activity and electric fields that show the occurrence of E pulses temporally close (within 250 μs) to individual optical recoil leaders similar to those observed by *Saba et al.* [2008] (as seen in section 3.1 and Figure 1). As shown in Figure 9, when the pulses associated with individual recoil leaders (Figure 1) are compared to those observed in Case 5 (Figure 6) and Case 6 (Figure 8), one can argue that they are similar. The waveforms of all pulses were unipolar with durations that ranged from 1.6 to 5.0 μs, even though those associated with Case 5 (Figures 9c and 9d) had opposite polarity when compared to the others. Additionally, these fast pulses resemble the microsecond-scale electric field variations that occur in a large fraction of the *M* changes during ground flashes and in the *K* changes produced by both intracloud and cloud-to-ground discharges [e.g., *Krider et al.*, 1975; *Bils et al.*, 1988; *Thottappillil et al.*, 1990; *Rakov et al.*, 1992; *Campos and Saba*, 2012]. Some authors have argued that *K* changes and recoil leaders (or "recoil streamers") are, in fact, either the same or similar physical process [e.g., *Rhodes and Krehbiel*, 1989; *Mazur et al.*, 1995; *Shao et al.*, 1995; *Mazur*, 2002]. In this case, and considering the apparent relationship between recoil leaders and the pulse activity preceding each luminous process, a more detailed discussion on the nature of type β_2 stepped leaders is given in the next section.

4. On the Nature of Schonland's Dart Streamers

Because *Schonland et al.* [1938] are the only investigators who have observed and described type β_2 leaders, their works are the only source of information about their physical characteristics. There are basically two features in their behavior that are key:

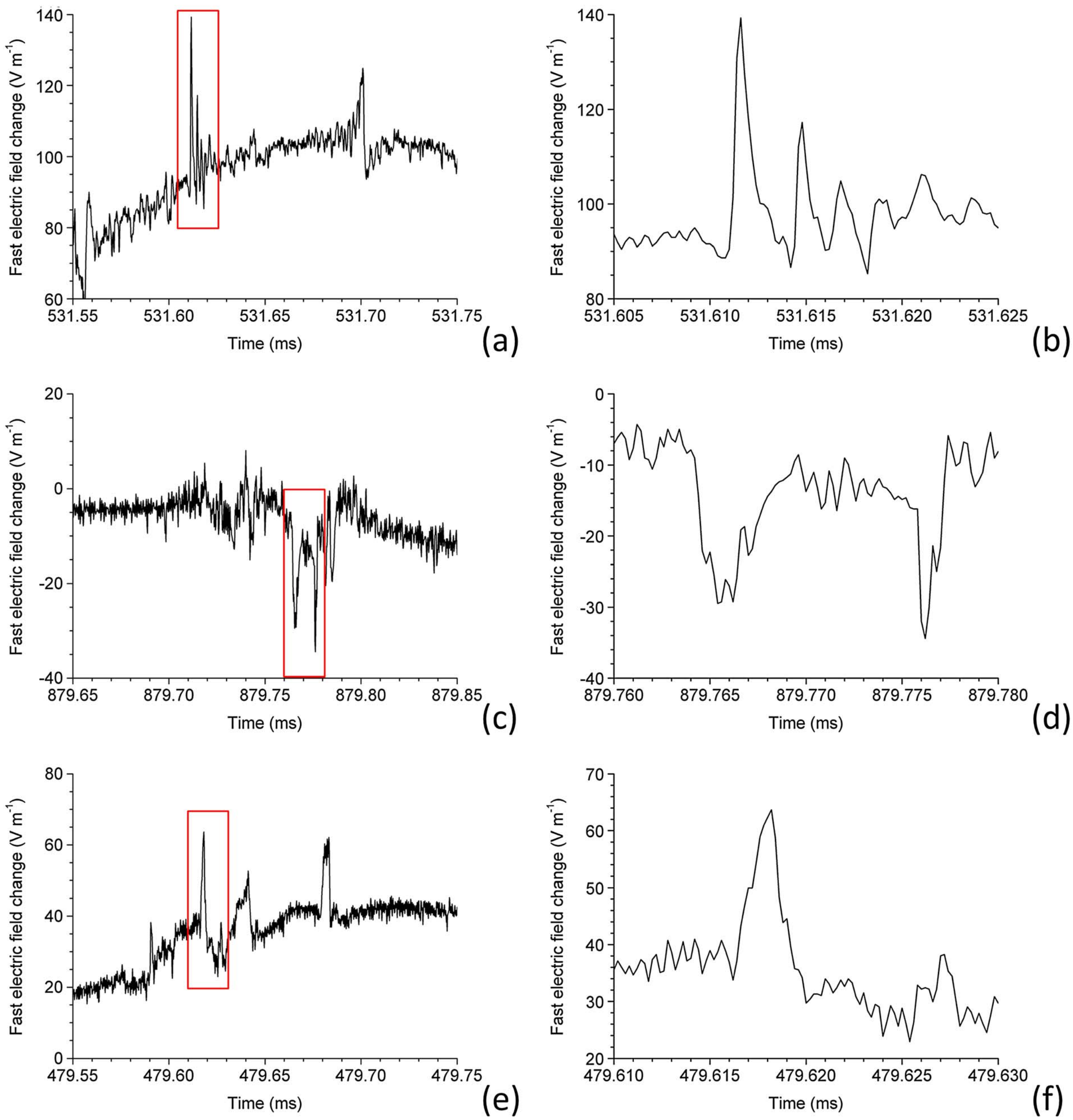

Figure 9. Detailed comparison of the individual peaks of (a and b) recoil leaders of the same event shown in frame e of Figure 1, (c and d) two of the peaks that preceded the luminous process of Case 5, and (e and f) two of the peaks that preceded Case 6. The red rectangles in Figures 9a, 9c, and 9e indicate the location of the regions that are shown in greater detail in Figures 9b, 9d, and 9f, respectively.

1. Since the step interval in regular stepped leaders (on the order of 50 μs) "is determined by the conditions at the tip of the leader" and "in the case of the steps due to dart streamers in the type β_2 leader the interval, as shown by Table 2, is on the order of 0.01 s," which is clearly a much longer interval, this characteristic has led Schonland et al. to "suggest that these streamers are controlled by processes within the cloud itself, being actually new leader discharges from new centers of charge within the cloud" [*Schonland et al.*, 1938, p. 463 and Table 2]. No further hypotheses are offered about which process or processes (that were known at that time) occurred within the cloud and might be responsible for producing the dart streamers.
2. Because the time intervals between successive dart streamers within a β_2 leader are similar to the intervals between successive strokes in a normal CG flash, Schonland et al. conclude that both processes are similar, and if this is true, they also suggest that "the slowness of the leader process thus causes the type β_2 first stroke

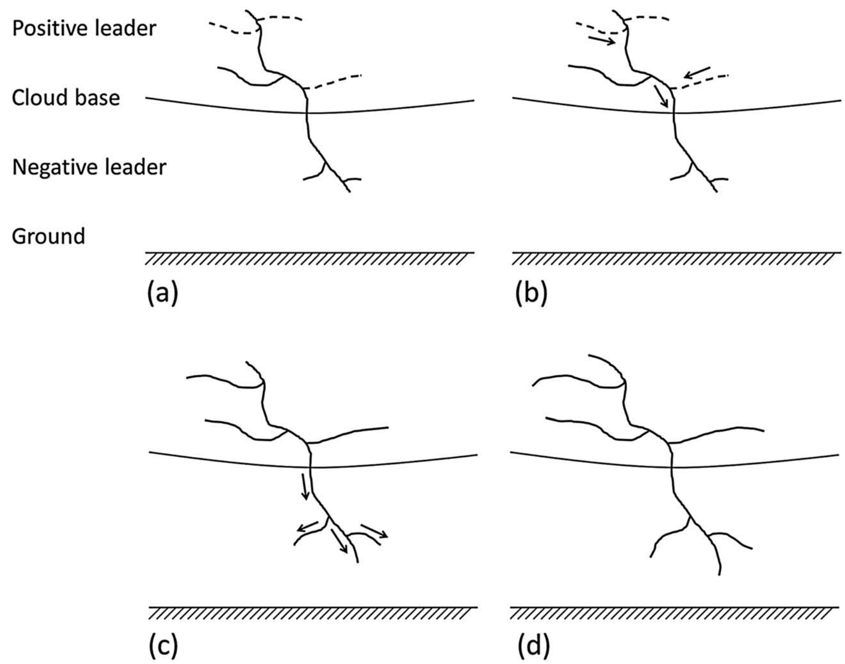

Figure 10. (a–d) Sketch of the formation of a β_2 stepped leader (see text for a detailed description). The solid lines show active channel segments, the dashed lines indicate previous branches in the positive portion of the bidirectional leader (where the current has been cut off), and the arrows show the recoil leaders, the subsequent luminous processes, and their direction of propagation.

to embody in one stroke what would otherwise be two or more strokes from the cloud to ground." The last statement leads to a conclusion that the "type β_2 discharges would not be followed by many subsequent strokes" [*Schonland et al.*, 1938, p. 464]. This suggestion is supported by the fact that, among the four cases that they describe, three had no subsequent strokes and the fourth had only one.

The occurrence of fast electric field pulses coming from the cloud just before the onset of each luminous process supports (i) above. This observation adds to the similarity between RLs and the *K* changes in both intracloud and cloud-to-ground flashes [*Krider et al.*, 1975; *Bils et al.*, 1988; *Thottappillil et al.*, 1990; *Rakov et al.*, 1992]. It also suggests that the nature and origin of the dart streamers can be explained in the context of a bipolar and bidirectional leader. Here we suggest that a type β_2 negative leader is the visible manifestation of one or more negative recoil leaders that are initiated in positive channel branches inside the cloud during the formation of a negative cloud-to-ground flash, and they propagate below the cloud base, enhancing the luminosity of a lower, negative leader end before ground contact occurs.

After one or more RLs are initiated inside the cloud (by processes that are still unknown), they propagate throughout the system of previously ionized channels created by the bidirectional leader and that have gone through current cutoff. As for the RLs that were described by *Saba et al.* [2008], the RLs that create a β_2 leader propagate in a retrograde fashion, i.e., toward the origin of the bidirectional leader. Some of the RLs connect to an active branch of the positive leader of the double-ended lightning tree, which causes a luminous process that propagates toward the origin of the flash in a retrograde fashion. This sequence is similar to what has been proposed by *Mazur and Ruhnke* [2011] for the *M* components in tower-initiated upward lightning. When the RL is intense enough, it can propagate through the negative downward portion of the bidirectional leader, and the associated luminosity intensification will move toward the tip of the negative portion of the leader system during the stepped leader phase. This intense recoil of luminosity will appear as the dart streamer reported by *Schonland et al.* [1938] and that we have recorded using our high-speed camera during the final stages of a luminous process. The above sequence of development is illustrated in Figure 10: (a) the bidirectional leader begins to ionize an upward, horizontal channel that is positive inside the cloud while a downward negative channel forms and moves toward ground; (b) recoil leaders reilluminate the inactive branches of positive channels and propagate downward toward the point of origin; (c) the recoil leaders make contact with active branches of the positive leader and give rise to a fast luminous process that propagates through the lightning channel and eventually reaches the origin region and enhances the luminosity of the negative portion of the bidirectional leader. Eventually the RL reaches the lower tip of the leader system, which enables the luminosity to be recorded with a high-speed camera; and (d) when the sequence of events ends, both portions of the bidirectional leader channel continue to develop, until the negative leader reaches ground and initiates a return stroke.

The mechanism depicted in Figure 10 is consistent with the current bidirectional model of lightning formation [*Mazur*, 2002], wherein *M* components and dart leaders are recoil leaders that occur in channels in different situations or regimes [*Mazur and Ruhnke*, 2011]. The main evidence for this hypothesis has been discussed in detail in section 3.3.

Finally, in regard to Schonland's characteristic (ii) at the beginning of this section, we believe that Case 1, described in section 3.3, gives evidence that return strokes initiated by a type β_2 negative leader can be followed by a relatively large number of subsequent strokes, especially if the number is compared to the average number of strokes per flash or video multiplicity that has been documented in recent studies [e.g., *Saba et al.*, 2006; *Saraiva et al.*, 2010]. Additionally, the large number of recoil leaders observed by *Saba et al.* [2008, and supporting information] during the development of positive leaders to ground indicates that such a process might not transfer a charge that is comparable to that of a subsequent return stroke. *Campos et al.* [2014, Figure 16] have reported that the occurrence of recoil activity during a downward propagating positive leader does not affect the peak current of the positive return stroke that follows. It is also worth noting that it has not been possible to determine if the estimated peak current of the return stroke that follows is affected by the occurrence of a type β_2 leader given that only three cases had those currents reported by a LLS.

5. Summary and Concluding Remarks

We have described seven examples of type β_2 leaders in negative cloud-to-ground lightning flashes that add to the sample obtained in the seminal photographic study of *Schonland et al.* [1938]. Estimates of their 2-D propagation speed have enabled a comparison of their values with other types of lightning leaders. Analyses of their optical characteristics along with correlated electric field changes have provided new insights into the characteristics of type β_2 leader phenomena. From this analysis, we conclude that the stepped leader phases of a type β_2 leader are very similar to those in regular stepped leaders, and the dart streamers (using a terminology initially given by *Schonland et al.* [1938]) are similar to dart leaders in terms of both their optical signatures and propagation speeds, and this in turn implies that in-cloud recoil activity is responsible for their initiation. In the three cases for which electric field measurements were available, it has been possible to associate the inception of each dart streamer to a sequence of microsecond-scale pulses and electric field variations that are similar to the *K* changes during intracloud and cloud-to-ground flashes. Given these similarities, a hypothesis has been proposed about the nature of the dart streamers in the context of a bidirectional leader model. We have suggested that a recoil leader initiated within the positive network of channels can occur in or attach to one of the branches and initiate a luminous process that eventually propagates downward toward the leader origin, and enhance the luminosity throughout the negative portion of the channel until it reaches the tip and appears as the dart streamer, found by Schonland and coworkers and observed by us in high-speed video recordings.

By comparing the development speeds of the type β_2 leaders with the ones reported for normal stepped leaders, one can argue that the only difference between them is the occurrence of the dart streamers before ground contact is made. The inference made here that the dart streamers are produced by recoil leaders in the upper, in-cloud positive region of the bidirectional leader reinforces the idea proposed by *Beasley et al.* [1982] that there is only one type of stepped leader process. All other things being equal, the only distinctive factor (i.e., occurrence of dart streamers/luminous processes) is caused by a physical process (i.e., recoil leaders) that is independent from the stepped leader propagation mode.

Acknowledgments
We would like to thank K.L. Cummins for coordinating the field campaign in Tucson and the support provided by C. Weidman, S. Fleenor, W. Scheftic, J. Wilson, P. Shaw, C. Jones, and S. Fleenor as well as the assistance of A.C.V. Saraiva in data reduction. Also, the field campaign in São José dos Campos would not have been possible without the assistance of C. Schumann, C. Medeiros, R. Guedes, S. Viegas, and C. Lopes. The authors are also grateful to W. Schulz for providing the schematics and software used for the electric field sensor and data acquisition system. This research has been supported by CNPq and FAPESP through projects 475299/2003-5 and 03/08655-4, respectively, and by the NASA Kennedy Space Center, grant NNK06EB55G. L.Z.S.C. is also grateful to FAPESP for scholarship number 2010/02716-5. The authors are indebted P. Krehbiel and other two anonymous reviewers for their valuable comments and insights that greatly improved the original manuscript.

References

Ballarotti, M. G., M. M. F. Saba, and O. Pinto Jr. (2005), High-speed camera observations of negative ground flashes on a millisecond-scale, *Geophys. Res. Lett.*, *32*, L23802, doi:10.1029/2005GL023889.

Beasley, W., M. A. Uman, and P. L. Rustan Jr. (1982), Electric fields preceding cloud-to-ground lightning flashes, *J. Geophys. Res.*, *87*, 4883–4902, doi:10.1029/JC087iC07p04883.

Berger, K., and E. Vogelsanger (1966), Photographische Blitzuntersuchungen der Jahre 1955–1965 auf dem Monte San Salvatore, *Bull. Schweiz. Elektrotech. Ver.*, *57*, 599–620.

Biagi, C. J., K. L. Cummins, K. E. Kehoe, and E. P. Krider (2007), National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004, *J. Geophys. Res.*, *112*, D05208, doi:10.1029/2006JD007341.

Bils, J. R., E. M. Thomson, M. A. Uman, and D. Mackerras (1988), Electric field pulses in close lightning cloud flashes, *J. Geophys. Res.*, *93*, 15,933–15,940, doi:10.1029/JD093iD12p15933.

Brook, M., and T. Ogawa (1977), The cloud discharge, in *Lightning*, Physics of Lightning, vol. 1, edited by R. Golde, pp. 191–230, Academic Press, New York.

Campos, L. Z. S., and M. M. F. Saba (2009), Comment on "Computer simulations on sprite initiation for realistic models with higher-frequency surges" by T. Asano, T. Suzuki, Y. Hiraki, E. Mareev, M. G. Cho, and M. Hayakawa, *J. Geophys. Res.*, *114*, A12324, doi:10.1029/2009JA014335.

Campos, L. Z. S., and M. M. F. Saba (2012), Electric field waveforms of M components in negative and positive ground flashes: A comparative analysis, paper presented at 31st International Conference on Lightning Protection, ALDIS, Vienna, Austria, doi:10.1109/ICLP.2012.6344338.

Campos, L. Z. S., and M. M. F. Saba (2013), Visible channel development during the initial breakdown of a natural negative cloud-to-ground flash, *Geophys. Res. Lett.*, *40*, 4756–4761, doi:10.1002/grl.50904.

Campos, L. Z. S., M. M. F. Saba, O. Pinto Jr., and M. G. Ballarotti (2007), Waveshapes of continuing currents and properties of M-components in natural negative cloud-to-ground lightning from high-speed video observations, *Atmos. Res.*, *84*, 302–310, doi:10.1016/j.atmosres.2006.09.002.

Campos, L. Z. S., M. M. F. Saba, O. Pinto Jr., and M. G. Ballarotti (2009), Waveshapes of continuing currents and properties of M-components in natural positive cloud-to-ground lightning, *Atmos. Res.*, *91*, 416–424, doi:10.1016/j.atmosres.2008.02.020.

Campos, L. Z. S., M. M. F. Saba, T. A. Warner, O. Pinto Jr., E. P. Krider, and R. E. Orville (2014), High-speed video observations of natural cloud-to-ground lightning leaders – A statistical analysis, *Atmos. Res.*, *135–136*, 285–305, doi:10.1016/j.atmosres.2012.12.011.

Chen, M., N. Takagi, T. Watanabe, D. Wang, Z.-I. Kawasaki, and X. Liu (1999), Spatial and temporal properties of optical radiation produced by stepped leaders, *J. Geophys. Res.*, *104*, 27,573–27,584, doi:10.1029/1999JD900846.

Cummins, K. L., and M. J. Murphy (2009), An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the U.S. NLDN, *IEEE Trans. Electromagn. Compat.*, *51*, 499–518, doi:10.1109/TEMC.2009.2023450.

Fleenor, S. A., C. J. Biagi, K. L. Cummins, E. P. Krider, and X. M. Shao (2009), Characteristics of cloud-to-ground lightning in warm-season thunderstorms in the Central Great Plains, *Atmos. Res.*, *91*, 333–352, doi:10.1016/j.atmosres.2008.08.011.

Jordan, D. M. (1990), Relative light intensity and electric field intensity of cloud to ground lightning, PhD thesis, Univ. of Florida, Gainesville.

Jordan, D. M., V. P. Idone, V. A. Rakov, M. A. Uman, W. H. Beasley, and H. Jurenka (1992), Observed dart leader speed in natural and triggered lightning, *J. Geophys. Res.*, *97*, 9951–9957, doi:10.1029/92JD00566.

Kasemir, H. W. (1950), Qualitative Ubersicht uber Potential-, Feld- und Ladungsverhaltnisse bei einer Blitzentladung in der Gewitterwolke, in *Das Gewitter*, edited by H. Israel, pp. 112–126, Akad. Verlagsges, Leipzig, Germany.

Kasemir, H. W. (1960), A contribution to the electrostatic theory of a lightning discharge, *J. Geophys. Res.*, *65*, 1873–1878, doi:10.1029/JZ065i007p01873.

Kawasaki, Z. I., and V. Mazur (1992), Common physical processes in natural and triggered lightning in winter storms in Japan, *J. Geophys. Res.*, *97*, 12,935–12,945, doi:10.1029/92JD01255.

Kawasaki, Z., S. Yoshihashi, and L. J. Ho (2002), Verification of bi-directional leader concept by interferometer observations, *J. Atmos. Electr.*, *22*, 55–79.

Krider, E. P., G. J. Radda, and R. C. Noggle (1975), Regular radiation field pulses produced by intracloud lightning discharges, *J. Geophys. Res.*, *80*, 3801–3804, doi:10.1029/JC080i027p03801.

Lu, W., Y. Zhang, J. Li, D. Zheng, W. Dong, S. Chen, and F. Wang (2008), Optical observations on propagation characteristics of leaders in cloud-to-ground lightning flashes, *Acta Meteorol. Sin.*, *22*, 66–77.

Mach, D. M., and W. D. Rust (1997), Two-dimensional speed and optical risetime estimates for natural and triggered dart leaders, *J. Geophys. Res.*, *102*, 13,673–13,684, doi:10.1029/97JD00926.

Mazur, V. (1989), Triggered lightning strikes to aircraft and natural intracloud discharges, *J. Geophys. Res.*, *94*, 3311–3325, doi:10.1029/JD094iD03p03311.

Mazur, V. (2002), Physical processes during the development of lightning flashes, *C. R. Phys.*, *3*, 1393–1409.

Mazur, V., and L. H. Ruhnke (2011), Physical processes during development of upward leaders from tall structures, *J. Electrostat.*, *69*, 97–110, doi:10.1016/j.elstat.2011.01.003.

Mazur, V., P. R. Krehbiel, and X. M. Shao (1995), Correlated high-speed video and radio interferometric observations of a cloud-to-ground lightning flash, *J. Geophys. Res.*, *100*, 25,731–25-753, doi:10.1029/95JD02364.

Mazur, V., L. H. Ruhnke, T. A. Warner, and R. E. Orville (2013), Recoil leader formation and development, *J. Electrostat.*, *71*, 763–768, doi:10.1016/j.elstat.2013.05.001.

Naccarato, K. P., and O. Pinto Jr. (2009), Improvements in the detection efficiency model for the Brazilian lightning detection network (BrasilDAT), *Atmos. Res.*, *91*, 546–563, doi:10.1016/j.atmosres.2008.06.019.

Nag, A., and V. A. Rakov (2009), Some inferences on the role of lower positive charge region in facilitating different types of lightning, *Geophys. Res. Lett.*, *36*, L05815, doi:10.1029/2008GL036783.

Orville, R. E., and V. P. Idone (1982), Lightning leader characteristics in the Thunderstorm Research International Program (TRIP), *J. Geophys. Res.*, *87*, 11,177–11,192, doi:10.1029/JC087iC13p11177.

Rakov, V. A., and M. A. Uman (2003), *Lightning: Physics and Effects*, 687 pp., Cambridge Univ. Press, New York.

Rakov, V. A., R. Thottappillil, and M. A. Uman (1992), Electric field pulses in K and M changes of lightning ground flashes, *J. Geophys. Res.*, *97*, 9935–9950, doi:10.1029/92JD00797.

Rhodes, C., and P. R. Krehbiel (1989), Interferometric observations of a single stroke cloud-to-ground flash, *Geophys. Res. Lett.*, *16*, 1169–1172, doi:10.1029/GL016i010p01169.

Rhodes, C. T., X. M. Shao, P. R. Krehbiel, R. J. Thomas, and C. O. Hayenga (1994), Observations of lightning phenomena using radio interferometry, *J. Geophys. Res.*, *99*, 13,059–13,082, doi:10.1029/94JD00318.

Richard, P., A. Delannoy, G. Labaune, and P. Laroche (1986), Results of spatial and temporal characterization of the VHF-UHF radiation of lightning, *J. Geophys. Res.*, *91*, 1248–1260, doi:10.1029/JD091iD01p01248.

Saba, M. M. F., M. G. Ballarotti, and O. Pinto Jr. (2006), Negative cloud-to-ground lightning properties from high-speed video observations, *J. Geophys. Res.*, *111*, D03101, doi:10.1029/2005JD006415.

Saba, M. M. F., K. L. Cummins, T. A. Warner, E. P. Krider, L. Z. S. Campos, M. G. Ballarotti, O. Pinto Jr., and S. A. Fleenor (2008), Positive leader characteristics from high-speed video observations, *Geophys. Res. Lett.*, *35*, L07802, doi:10.1029/2007GL033000.

Saba, M. M. F., L. Z. S. Campos, E. P. Krider, and O. Pinto Jr. (2009), High-speed video observations of positive ground flashes produced by intracloud lightning, *Geophys. Res. Lett.*, *36*, L12811, doi:10.1029/2009GL038791.

Saba, M. M. F., W. Schulz, T. A. Warner, L. Z. S. Campos, C. Schumann, E. P. Krider, K. L. Cummins, and R. E. Orville (2010), High-speed video observations of positive lightning flashes to ground, *J. Geophys. Res.*, *115*, D24201, doi:10.1029/2010JD014330.

Saraiva, A. C. V., M. M. F. Saba, O. Pinto Jr., K. L. Cummins, E. P. Krider, and L. Z. S. Campos (2010), A comparative study of negative cloud-to-ground lightning characteristics in São Paulo (Brazil) and Arizona (United States) based on high-speed video observations, *J. Geophys. Res.*, *115*, D11102, doi:10.1029/2009JD012604.

Saraiva, A. C. V., et al. (2014), High speed video and electromagnetic analysis of two natural bipolar cloud-to-ground lightning flashes, *J. Geophys. Res. Atmos.*, *119*, doi:10.1002/2013JD020974.

Schonland, B. F. J. (1938), Progressive lightning, 4, The discharge mechanisms, *Proc. R. Soc. London*, *A164*, 132–150.

Schonland, B. F. J. (1956), The lightning discharge, *Handb. Phys.*, *22*, 576–628.

Schonland, B. F. J., D. J. Malan, and H. Collens (1935), Progressive lightning, 2, *Proc. R. Soc. London*, *A152*, 595–625.

Schonland, B. F. J., D. J. Malan, and H. Collens (1938), Progressive lightning, 6, *Proc. R. Soc. London*, *A168*, 455–469.

Shao, X. M. (1993), The development and structure of lightning discharges observed by VHF radio interferometer, PhD thesis, New Mexico Inst. of Mining and Technol., Socorro.

Shao, X. M., P. R. Krehbiel, R. J. Thomas, and W. Rison (1995), Radio interferometric observations of cloud-to-ground lightning phenomena in Florida, *J. Geophys. Res.*, *100*, 2749–2783, doi:10.1029/94JD01943.

Thomson, E. M., M. A. Uman, and W. H. Beasley (1985), Speed and current for lightning stepped leaders near ground as determined from electric field records, *J. Geophys. Res.*, *90*, 8136–8142, doi:10.1029/JD090iD05p08136.

Thottappillil, R., V. A. Rakov, and M. A. Uman (1990), K and M changes in close lightning ground flashes in Florida, *J. Geophys. Res.*, *95*, 18,631–18,640, doi:10.1029/JD095iD11p18631.

Warner, T. A. (2012), Observations of simultaneous upward lightning leaders from multiple tall structures, *Atmos. Res.*, *117*, 45–54, doi:10.1016/j.atmosres.2011.07.004.

Workman, E. J., J. W. Beams, and L. B. Snoddy (1936), Photographic study of lightning, *J. Appl. Phys.*, *7*, 375–379.