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HIGH-SPEED VIDEO AND ELECTRIC FIELD OBSERVATIONS OF TYPE BETA-2 LEADERS IN NEGATIVE LIGHTNING: A MANIFESTATION OF RECOIL LEADERS INITIATED INSIDE THE CLOUD?

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ABSTRACT

Schonland et al. (Progressive lightning, 6, *Proc. Roy. Soc. (London)*, *A168*, 455-469, 1938), in their seminal streak camera studies of lightning, have identified four events of a peculiar type of negative stepped leader that they termed "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". During two different campaigns between 2007 and 2011 in Tucson, Arizona, USA, and in São José dos Campos, São Paulo, Brazil, we recorded seven downward leaders that fit in the type β_2 description given by Schonland et al. (1938). All cases occurred between about 5 and 32 km from a high-speed camera that was operating at 4000 frames per second and three of them could also have their electric field changes measured. All the "dart streamers" that we observed had speeds between 10^6 and 10^7 m s^{-1}, in agreement with previous observations of recoil leaders (RLs). Also, during the development of the three cases whose electric field change data was available it was possible to identify a sequence of microsecond-scale pulses preceding the development of the Considering the similarities in the optical and electric field signatures of both phenomena, we propose that the type β_2 negative leaders are the visible manifestation of the development of RLs that were initiated inside the cloud and propagate below the cloud-base during the development of a bipolar, bidirectional leader that precedes a lightning flash to ground. The RLs are initiated in and propagate through channels that were previously ionized by the in-cloud positive portion of a bidirectional leader, eventually connecting to one of its active branches. When they do an intense return pulse of luminosity that optically appears as the dart streamer reported by Schonland et al. (1938) is produced and propagates until it reaches the lower tip of the negative downward portion. After the RL process is completed the downward negative stepped leader portion of the bidirectional leader continues its development normally, with the possibility of occurrence of other RLs, until it reaches the ground and produces a return stroke.

1. INTRODUCTION

In negative cloud-to-ground (–CG) flashes, first strokes and subsequent strokes that follow a new channel to the ground are initiated by stepped leaders. During its development it presents very faint individual steps, responsible for its terminology. Based on the seminal streak camera studies of lightning, Schonland (1938) has organized the stepped-leaders in two categories: α- and β-type leaders. The type α leaders presented uniform downward speeds on the order of 10^5 m s^{-1} with steps showing small variation of length and brightness; they were also the most common type observed, representing 55-70% of the cases (Schonland, 1938, 1956). The type β leaders, on the other hand, present a discontinuity in its downward movement. At the first phase, near the cloud base, the leader has brighter and longer steps (compared to those observed in type α leaders) and higher speeds, on the order of 10^6 m s^{-1}. At the second phase, as it approaches the ground, the β-leader behaves like an α-leader, decreasing its speed and brightness and developing shorter steps.

Furthermore, Schonland et al. (1938) have divided the type β leaders into two variants, subtypes β_1 and β_2. The type β_1 leader is the most common and was described above as the type β leader (Schonland, 1938). The 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). They have observed only four cases using a streak-camera; two cases presented one dart streamer, one case presented two and one wasn't detailed in their work. Two of these four cases had an increase on the leader speed after

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the occurrence of the dart streamer (flashes 32 and 102), one had a decrease (flash 92) and one did not present any measurable change (flash BX) (Schonland et al., 1938, Figure 9). In only one case the dart streamer speed could be estimated as being greater than 2.0 x 10^6 m s^{-1} (Schonland et al., 1938, p. 461). A photograph taken by Workman et al. (1936, Figure 1) using a slow-moving film camera is probably the first register of this phenomenon, described as a "valuable illustration of the type β_2" by Schonland et al. (1938, p. 464). As pointed out by Rakov and Uman (2003, p. 123), apparently no β_2 cases were registered in further photographic studies (e.g., Berger and Vogelsanger,1966; Orville and Idone, 1982; Jordan, 1990). Two possible reports of β_2 cases, though, are the investigations by Shao et al. (1995) and Mazur et al. (1995), both using data from a radio interferometric system (detailed by Rhodes et al., 1994). Shao et al. (1995, pp. 2751-2752) have described a multiple-stroke cloud-to-ground flash that presented three "attempted leaders" during the 50-ms interval between the first and second return strokes. Each of these attempted leaders began in the same region as the leader of the first stroke and progressed rapidly towards the ground (the speed was not estimated) but lasting between 1 and 2 ms and dying out before reaching the ground. The radiation maps showed that the first attempted leader followed the path of the initial leader (radiating only from intermittent locations along its path) and the second one was displaced to the left of the first attempt (radiating continuously along its path). The third attempted leader described the same path as the second one but radiated only from the upper and lower parts of the channel. Finally, seventeen milliseconds afterwards a new leader succeeded reaching the ground. It took only 300-400 μs for the leader to describe the channel developed by the three previous attempted leaders and then more than 3 ms to propagate through the remaining distance to the ground. Shao et al. (1995) then define the last leader as being of the dart-stepped type with a different ground contact point from the first stroke of this flash. Mazur et al. (1995) have also observed a similar behavior in the dart-stepped leader of the third stroke of a six-stroke flash observed by a high-speed camera (1000 frames per second) in addition to the radio interferometric system. They have said that the channel of the third stroke dart-stepped leader "brightened substantially 3 ms before reaching ground (frame 233, Figure7)" 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). Further in their work it is said 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 through 6c)" (Mazur et al., 1995, p. 25,736 and Figure 6). They have also highlighted the similarity of this fast in-cloud streamer to those reported by Shao (1993) and Rhodes et al. (1994) during the development of leaders. No development speed estimates were presented for that leader process. We believe that the descriptions of both cases agree with the type β_2 leader observations made by Schonland et al. (1938) with the difference that it occurred in a dart-stepped leader instead of a first stroke stepped leader. The "attempted leader" (Shao et al., 1995, pp. 2751-2752) or "M-type event" (Mazur et al., 1995, p. 25,731) matches the description of the phenomenon named *dart streamer* by Schonland et al. (1938), which catches up with the tip of the stepped leader (or, in these cases, the dart-stepped leader during its final stepped phase). Neither works presented any speed estimate for this phenomenon that could be compared to the minimum value calculated by Schonland et al. (1938, p. 461). More recently, Lu et al. (2008, pp. 72-73), based on high-speed video data, have reported a case described as an attempted leader due to the similarity to what was described by Shao et al. (1995). This attempted leader, though, could also be the dart streamer of a type β_2 dart-stepped leader as it not only fits the description but also had presented a maximum speed of 1.1 x 10^6 m s^{-1}, comparable to the minimum speed estimate made by Schonland et al. (1938, p. 461) for the streamer of the flash 102 (2.0 x 10^6 m s^{-1}).

Beasley et al. (1982, p. 4901), based on electric field data and an extensive literature review, 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. (2012) have presented a preliminary analysis on how lightning downward leader speeds change with height and did not find any discernible evidences favorable to such categorization; even though 6% of the stepped leaders that were studied seemed to decelerate and could eventually fit in the type β description (a very low percentage compared to what was observed by Schonland (1938, 1956) there were no indications of such need. Other recent studies, though, have kept the historical terminology, but it is unclear whether or not they consider them as distinct physical processes (Lu et al., 2008; Nag and Rakov, 2009), so this question remains open. Even though we agree with the generalized point of view presented by Beasley et al. (1982), we have kept the type β_2 nomenclature not only for historical reasons but also in an attempt to differentiate it from the "regular" and most common stepped-leader process in which the presence of dart streamers is not observed.

Kasemir (1950, 1960) introduced the concept of 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) and consists in considering that "a lightning discharge is initiated with both positive and negative leaders progression simultaneously in opposite directions from its origin". Some evidences favorable to this model has been obtained with the help of experiments involving aircraft-triggered lightning discharges, whose results and interpretation were presented by Mazur (1989), and UHF interferometry observations of upward initiated lightning in Japan conducted by Kawasaki et al. (2002), among other investigations (e.g., Kawasaki and Mazur, 1992). With the development of the bidirectional leader concept the role of the physical process previously known as K-changes or recoil streamers has been reimagined. They have been renamed by Mazur (2002, p. 1394) as recoil *leaders* (RLs), once their present interpretation is that they consist of negative leaders, i.e., "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 basis to the construction of a more global view of lightning and its related processes, such as dart leaders, that can be viewed as RLs that reach the ground after channel current cutoff (Shao et al., 1995; Mazur, 2002), and M components, that can be viewed as RLs initiated in the branches of the developing positive leader during the continuing current period of a –CG flash (Mazur and Ruhnke, 2011). Early studies by Brook and Ogawa (1977) used electric field change measurements to analyze RLs in intracloud flashes, obtaining a speed estimate of 1.3 x 10^6 m s^{-1}. Afterwards, Richard et al. (1986) observed RLs through the use of VHF-UHF radiation data also from intracloud discharges; they propagated over distances that ranged from a few kilometers to more than 10 kilometers at speeds of the order of 10^7 m s^{-1}. More recently, Saba et al. (2008) presented optical data on RLs from high-speed video recordings of +CG flashes, observing their occurrence up to 120 milliseconds prior to the return stroke, and also after during the continuing current development. They have also noted that the RLs propagate in a retrograde fashion, i.e., towards the leader origin (Saba et al., 2008, Figures 4d, 4e and 4f) at a minimum estimated speed of 4 x 10^6 m s^{-1}. All these speed estimates are in fair agreement with what is observed not only in dart leaders of –CG flashes (e.g., Schonland et al., 1935; Orville and Idone, 1982; Jordan et al., 1992; Mach and Rust, 1997; Campos et al., 2012) but also in the single case of "dart streamer" whose speed could be estimated by Schonland et al. (1938) in a type β_2 negative leader.

In an attempt insert the type β_2 negative leaders in the generalized view of the physical processes involved in a lightning flash according to the bidirectional, zero-net-charge leader model, we present the hypothesis that these "dart streamers" reported by Schonland et al. (1938) are, actually, the manifestation of RLs initiated in the upper positive portion of the channel and that reaches the lower negative portion while it is still developing towards the ground as a stepped leader. In the following sections we describe the seven cases of type β_2 negative leaders that were observed by a digital high-speed camera and present our hypothesis in greater detail.

2. INSTRUMENTATION

The data presented in this work were provided by a single high-speed camera (all seven cases) and a fast electric field sensor (for three cases) during two field campaigns aiming to study the characteristics of CG flashes. Four cases were observed as part of a campaign conducted in Tucson, Arizona, USA during August 2007 (described in detail by Saraiva et al., 2010), and three cases were recorded in São José dos Campos, São Paulo, Brazil, during February 2011.

2.1 ***High-speed cameras***

The imagery data used in this work were provided by a high-speed digital camera (Photron FASTCAM 512 PCI) set to operate with temporal resolution of 4000 frames per second (250 microseconds exposure time) and GPS time synchronization, providing time-stamped images with no frame-to-frame brightness persistence. Through a detailed comparison between the video data provided by the camera and simultaneously measured fast electric field (see description below) of six return strokes (recorded at either 4000 or 8000 frames per second) it has been shown that the time stamping is made at the beginning of a given frame. Such analysis has been necessary in order to validate the analysis presented in Section 3 of the present paper in which it is important to determine whether a given electric field pulse occurs before or after a process recorded by the camera.

We have used a triggering system based on a signal from an external source and, for the present study, this signal came from a button pressed by the camera operator. It is possible to set the pre- and post-trigger time within the total recording time of 2 seconds. The pre- and post-trigger times of 1 second each has proven to be long enough to prevent the first strokes to be missed and allow the complete recording of the lightning flash considering its total duration (Saraiva et al., 2010). In-depth discussions on the accuracy of high-speed cameras for the determination of lightning parameters are presented on previous works by Ballarotti et al. (2005) and Saba et al. (2006).

2.2 ***Fast electric field sensors***

For the three cases observed in São José dos Campos, in addition to the high-speed video data, we have used three flat plate antennas to measure electric-field changes produced by lightning. Two of these antennas were operated as fast electric-field change sensors with the help of an integrator/amplifier (with a bandwidth that ranges from 306 Hz to 1.5 MHz), a GPS receiver for temporal synchronization, and a data acquisition system that operates at a sampling rate of 5 MS/s on each channel and a 12-bit analog/digital (A/D) converter. In order to guarantee enough sensitivity without the risk of losing data due to saturation, both antennas were operated simultaneously using integrator/amplifier circuits with sensitivities that are different by a factor of 10. The third antenna was connected to the same data acquisition apparatus (GPS and A/D converter) but with a different integrator amplifier circuit which was configured as a slow electric-field change sensor.

2.3 *Lightning location system*

For the determination of channel lengths and two-dimensional (2-D) speeds of the type β_2 leaders analyzed in this work it is necessary to know the geometric characteristics of the camera and the lenses used, and the distance between the observation site and the flash. This last parameter, as well as stroke polarity and return stroke peak current estimate, was obtained through data provided by the National Lightning Detection Network (NLDN) for the observation site at Tucson and by the Brazilian Lightning Detection Network (BrasilDAT) for the site at São José dos Campos. The stroke matching between high-speed camera and lightning locating system (LLS) data was done by GPS time synchronization (Ballarotti et al., 2005; Saba et al., 2006(and the observation sites are located in two regions that are well covered by their respective LLS (Cummins and Murphy, 2009; Naccarato and Pinto, 2009).

3. OBSERVATIONS AND DESCRIPTIVE ANALYSIS

The periods in which each leader case propagates as a regular stepped leader or dart leader we will be referred as *stepped leader phase* or *dart leader phase*, respectively. Even though we have decided to keep the historical denomination for the type β_2 leaders, from now on we will refer to the *dart streamers*, first described by Schonland et al. (1938), as *recoil leaders*, according to the hypothesis that will be presented in section 3.4. Also, in order to keep an uniform terminology when measuring 2-D of each leader, we will make use of the definitions presented by Saba et al. (2008, p. 2), in which *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”. Table 1 presents a summary of the characteristics and parameters of all seven cases that we have observed. Cases 1 and 6 were selected to be described in detail.

Table 1. Summary of the general characteristics of the seven cases analyzed in this work. TUS stands for Tucson, SJC for São José dos Campos, N/A for not available, SC for same channel, NC for new channel, I_p for estimated peak current, RL for recoil leader and SL for stepped leaders. The cases whose distances are marked with an asterisk were not detected but could be estimated based on a stroke within the same flash that followed the same channel and were detected. In cases 1, 6 and 7 only the minimum average RL speeds could be calculated.

Case #	Location	Stroke order	Distance (km)	I_p (kA)	Average SL 2-D speed (10^5 m s^{-1})	# of RLs	Average RL 2-D speed (10^5 m s^{-1})
1	TUS	1	12.3	–13	3.47	2	104 (*min.*)
2	TUS	1	31.5*	N/A	0.46	4	38.3
3	TUS	2 (NC)	29.6	–14.5	1.53	2	106
4	TUS	2 (SC)	12.3*	N/A	10.8	1	94.9
5	SJC	2 (NC)	14.6*	N/A	2.37	2	114
6	SJC	1	5.90	–12.0	1.99	1	45.3 (*min.*)
7	SJC	5 (NC)	17.5*	N/A	1.84	3	91.7 (*min.*)

3.1 *Detailed analysis: Case 1*

Case 1 has occurred on 07/25/2007 at 20h37min53s (UT) in Tucson. It has presented 8 strokes, all of them in the same channel. The first stroke was detected by the NLDN (with estimated peak current $I_p = -13$ kA, at a distance D = 12.3 km from the camera) and was initiated by a type β_2 leader. The eighth stroke was also detected ($I_p = -8.4$ kA, D = 13.6 km). This case has presented two recoil leaders and had an abrupt decrease in its stepped leader phase speed after the first one, but after the second RL the speed remained essentially the same. The temporal resolution of the camera was not high enough to make it possible to identify a pause in the propagation of the stepped leader phases before the initiation of each RL, differently from flash 92 observed by Schonland et al. (1938), which presented an apparent pause of 9 milliseconds before the RL is observed. Figure 1 shows a sequence of sectioned frames illustrating each phase of Case 1. Table 2 presents a detailed description of each phase of this case, correlating time, height and speed. The graphs in Figure 2 correlate the temporal variation of speed and luminosity as the leader develops towards the ground. The luminosity-versus-time graph was obtained through a computational algorithm developed and detailed by Campos et al. (2007, 2009) that is capable of calculating the average of pixels values for the channel region in each frame.

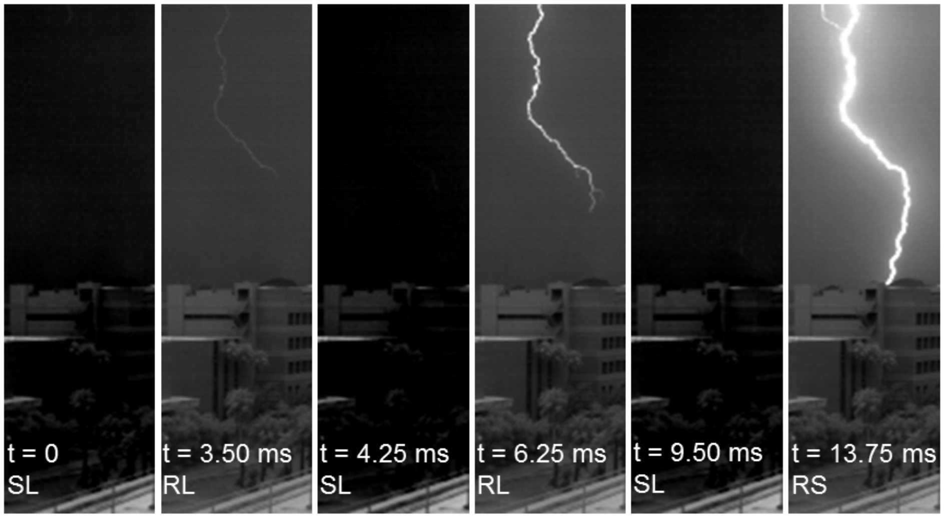

Figure 1. Sequence of sectioned frames illustrating Case 1. SL stands for the stepped leader phase, RL for recoil leader and RS for return stroke. The contrast was enhanced in the frames that show the stepped leader phases in order to facilitate the visualization of the very faint leader tip.

Table 2. Average 2-D speeds (for each phase) and leader tip height ranges for the Case 1. Time t = 0 was taken at the first frame in which the leader tip was visible. SL stands for stepped leader phase and RL for recoil leader. Only the minimum speed could be estimated for the first recoil leader.

Time (ms)	**Phase type**	**Height (m)**	**2-D speed (x 10^5 ms^{-1})**
0 – 3.25	SL	3580 – 2230	7.10
3.25 – 3.50	RL (1)	1690	92.3 *(min.)*
3.75 – 6.00	SL	1630 – 1410	1.72
6.00 – 6.25	RL (2)	1260	116
6.25 – 11.00	SL	1240 – 570	1.67
13.75	*Return Stroke*		

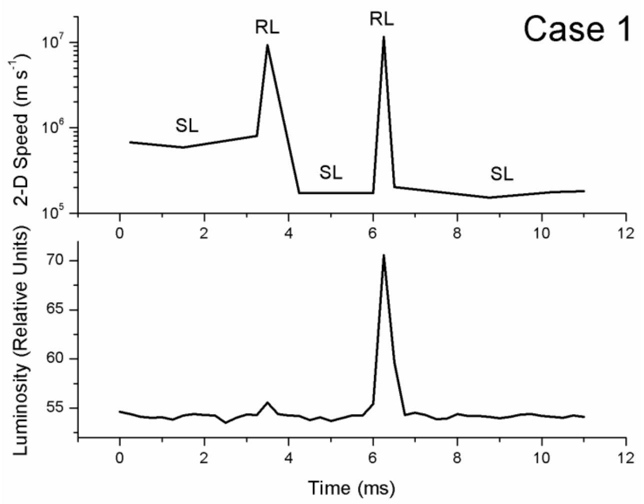

Figure 2. Temporal evolution of leader speed (above) and luminosity (below) for Case 1. In time t = 0 the frame in which the leader was first visible in the camera field-of-view was recorded and the return stroke occurred at t = 13.75 ms. SL stands for the stepped leader phase and RL stands for recoil leader. The first recoil leader (t = 3.50 ms) could have only its minimum speed estimated.

3.2 *Detailed analysis: Case 6*

Our Case 6 has occurred on 02/13/2011 at 18h44min10s (UT) in São José dos Campos and has presented a forked stroke initiated by a type β_2 stepped leader. The channel section that is closer to the camera and was the first to touch the 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) could be detected by the BrasilDAT (I_p = –12.0 kA, D = 5.90 km) and, for this reason, was analyzed in detail. The farther channel section has touched the ground at approximately t = 484.265 ms (one frame later than the closer section, as seen by the camera).

Figure 3 presents time-correlated data on leader tip height, two-dimensional speed, channel luminosity and fast electric field change for Case 6, and Table 3 summarizes all partial 2-D speed measurements provided by the high-speed video data. The RL that occurs between t = 479.750 ms and t = 480.000 ms in the closer channel section could also be seen in the farther section during the same period. Similarly to Case 5, even though data from a slow electric field sensor was available, it was mostly unresponsive to the occurrence of RLs and we have decided not to present it here. A more detailed comparison between the high-speed video record (sectioned frames) and the fast electric field data is presented in Figure 4. Similarly to what was seen on Case 5, the sequence of frames (c), (d) and (e) indicates that the electric field pulses precede the development of the RL towards the lower leader tip below cloud base. Due to this fact and considering that for the temporal resolution of the camera the RL occurred simultaneously on both channel sections we believe that they shared a common genesis inside the cloud. Six individual 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 microseconds to 14.2 microseconds, with a mean of 6.1 microseconds. These values are in good agreement with the pulses observed during the second RL of Case 5.

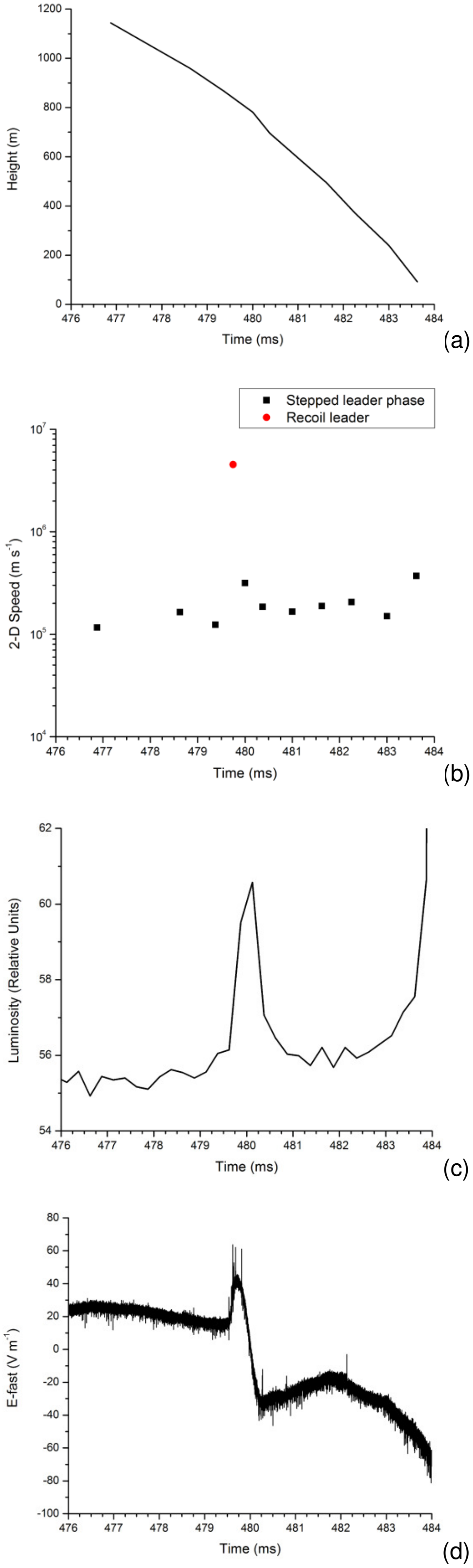

Figure 3. Time-correlated data on leader tip height, two-dimensional speed, channel luminosity and fast electric field change for Case 6. The return stroke occurs approximately at time t = 484.115 ms (not shown in the graphs).

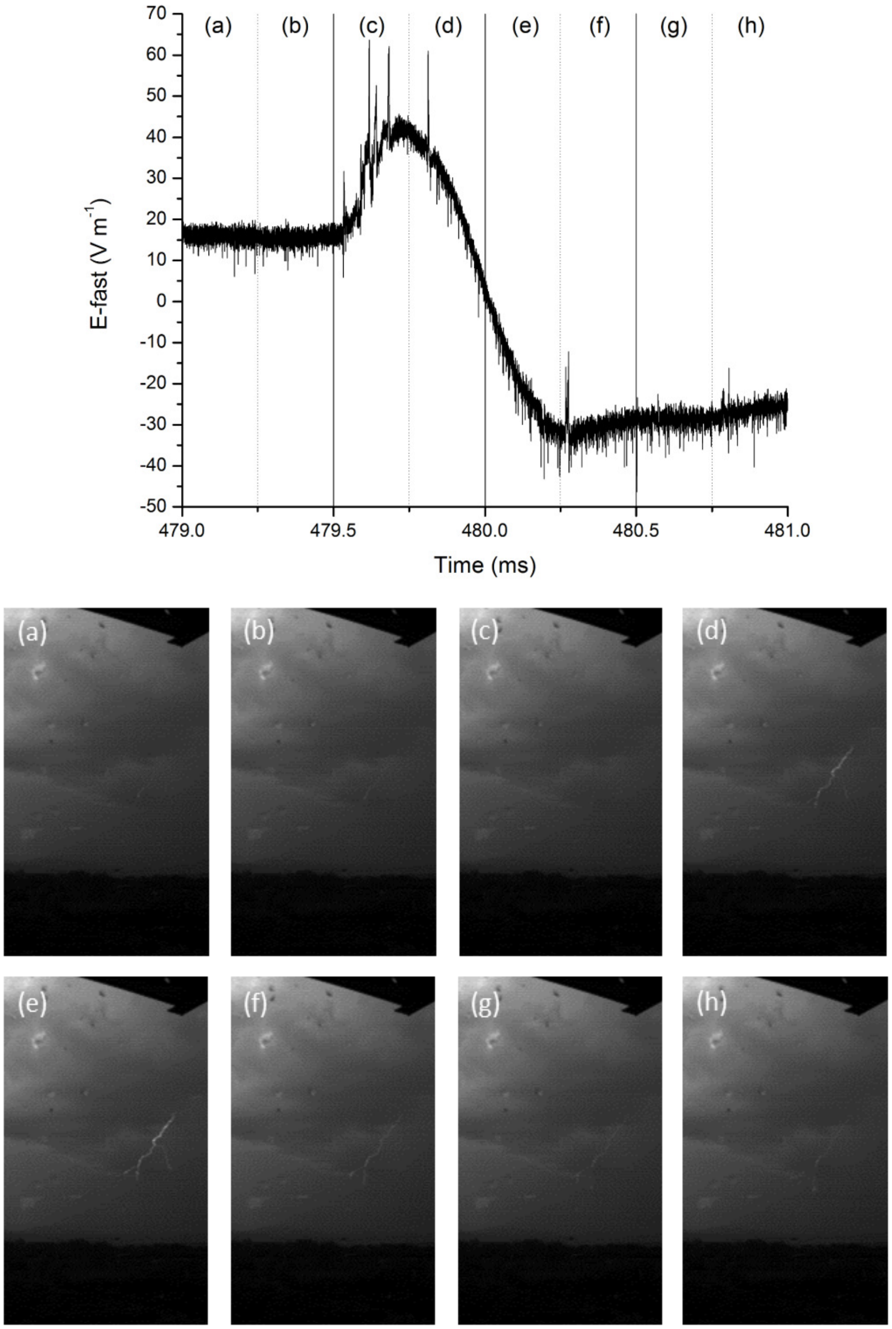

Figure 4. Detailed comparison between fast electric field data and high-speed video (sectioned frames) of the only recoil leader produced during the development of Case 6.

Table 3. Partial 2-D speeds and leader tip height ranges for Case 6. Time t = 0 was taken at the beginning of the second in which the whole leader process occurred as provided by the GPS synchronization, with the leader tip being first visible at t = 475.500 ms and the return stroke occurring at t = 484.000 ms. SL stands for stepped leader phase and RL for recoil leader. Only the minimum speed could be estimated for RL (1).

Time (ms)	**Phase type**	**Height (m)**	**2-D speed (x 10^5 ms^{-1})**
475.500 – 478.250	SL	1140	1.17
478.250 – 479.250	SL	960	1.64
479.250 – 479.750	SL	870	1.24
479.750 – 480.000	RL (1)	820	45.3 (*min.*)
480.000 – 480.250	SL	780	3.15
480.250 – 480.750	SL	700	1.86
480.750 – 481.500	SL	600	1.66
481.500 – 482.000	SL	500	1.88
482.000 – 482.750	SL	370	2.06
482.750 – 483.500	SL	240	1.50
483.500 – 484.750	SL	90	3.71
484.000	*Return Stroke*		

3.3 *General comments and summary of the observations*

An analysis of the speed measurements obtained for the seven cases of type β_2 leaders presented in this paper reveals that all the stepped leader phase speeds, which were between 0.22 x 10^5 to 7.10 x 10^5 m s^{-1}, fit within the range expected for "regular" 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., 2012). Similarly to what was reported by Schonland et al. (1938), there is no apparent uniformity of behavior of the stepped leader phase right after the development of each recoil leader (or *dart streamer*, as termed in their study), i.e., some cases accelerate, others decelerate and others do not present an appreciable change of speed, with no common discernible tendency.

Additionally, all recordings show that the recoil leaders that were observed in the seven type β_2 leader cases presented speeds ranging from 1.73 x 10^6 to 1.39 x 10^7 m s^{-1}, compatible not only with the estimate of minimum speed presented by Schonland et al. (1938) (2.0 x 10^6 ms^{-1}) but also with previous studies on both negative dart leaders (e.g., Schonland et al., 1935; Orville and Idone, 1982; Jordan et al., 1992; Mach and Rust, 1997; Campos et al., 2012) and recoil leaders that retraced channel segments previously ionized by positive leaders (Brook and Ogawa, 1977; Richard et al., 1986; Saba et al., 2008). This similarity serves as one of the basis of the hypothesis presented in the following section, in which we try to explain the type β_2 leader process in the wider context of the bidirectional leader concept.

Schonland et al. (1938, Table II and p. 463) observed time intervals between RLs ranging from 3 to 9 milliseconds, which made them speculate that their occurrence "are controlled by processes within the cloud itself". All recordings indicate that the range of time intervals between RLs observed in the present paper goes from 1.75 to 18.5 milliseconds (with a mean of approximately 9.6 ms). Even though only four out of the eight intervals fit in the range observed by them, we believe that the results of both studies are coherent. On the other hand, the qualitative physical description presented by Schonland et al. (1938, p.464) would imply that "type β_2 discharges would not be followed by many subsequent strokes", an assumption that they believe is 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 so clear in the dataset we have analyzed: Case 1 is initiated by a type β_2 leader and had seven subsequent strokes; Case 2 was also initiated by a type β_2 leader and had two subsequent strokes; Case 3 occurred in the second stroke of a five-stroke flash, i.e., was followed by three strokes; Cases 4 and 5 occurred in the second stroke of three-stroke flashes, i.e., were followed by only one stroke; Case 6 had only one almost simultaneous stroke; and Case 7 occurred in the fifth stroke of a nine-stroke flash, i.e., was followed by four strokes. Additionally, it is not clear if there is any influence over the return stroke peak current when it is initiated by a β_2 leader; only Cases 1, 3 and 6 were detected either by the NLDN or by the BrasilDAT and all of them presented estimated peak current values that are close to the mean and median values for negative strokes (–13 kA, –14.5 kA and –12.0 kA, respectively) (Biagi et al., 2007; Fleenor et al., 2009).

Finally, the availability of electric field change data for Cases 5 through 7 made it possible to shed some additional light on the physical processes responsible for the RLs in type β_2 leaders. With only one exception, all the RLs that occurred in those cases were positively associated with electric field pulses that occurred prior to their development below cloud base towards the lower leader tip (as shown by Figures 4). Still, for the temporal resolution of our high speed camera, the electric field pulses observed in the exceptional case (not included in the present paper) probably had a dubious nature due to the relatively short dimension of the channel at that moment, which has caused the pulses to occur within the timespan of the video frame that first showed the illumination associated with the RL. These evidences indicate that the pulses are related to the genesis of the RLs inside the cloud and not to their development below cloud base. It is also worth mentioning the fact that these pulses are very similar to the microsecond-scale electric field variations reported in a fraction of M changes of ground flashes and K changes associated with both cloud and ground flashes (e.g., Krider et al., 1975; Bils et al., 1988; Thottappillil et al., 1990; Rakov et al., 1992). Such variations can be either unipolar or bipolar with irregular waveforms, present durations of a few microseconds and are usually grouped in sequences of a few hundreds of microseconds. An analysis of Figures 4 (along with the other observed events) shows that the pulses associated with RLs in our study would fit in the description provided by the above mentioned researchers. Additionally, some authors defend that K changes and RLs (or other equivalent terminology, such as 'recoil streamers') are, in fact, the same physical process (e.g., Rhodes and Krehbiel, 1989; Mazur et al., 1995; Shao et al., 1995; Mazur, 2002). In this scenario, further and more detailed discussion concerning the nature of the type β_2 leaders are presented in the following section.

3.4 *Suggested hypothesis*

For the determination of channel lengths and two-dimensional (2-D) speeds of the type β_2 leaders analyzed in this work it is necessary to know the geometric characteristics of the camera and the lenses used, and the distance between the observation site and the flash. This last parameter, as well as stroke polarity and return stroke peak current estimate, was obtained through data provided

Due to the fact that Schonland et al. (1938) are the only investigators who have observed and identified cases of type β_2 leaders, they are currently the only source for discussions concerning the characteristics and physical nature of this phenomenon. There are basically two speculative comments concerning this issue in their original work:

(i) By comparison with the step-interval observed in regular stepped leaders (of the order of 50 microseconds), which "is determined by conditions at the tip of the leader", they say that "in the case of the steps due to dart streamers in the type β_2 leader the interval, as shown by Table II, is of the other of 0.01 s", which has induced them to "suggest that these streamers are controlled by processes within the cloud itself, being actually new leader discharges from new centres of charge within the cloud" (Schonland et al., 1938, Table II and p. 463). No speculation is presented concerning which process or processes (known at that time) within the cloud could be responsible for the occurrence of the dart streamers.

(ii) Schonland et al. (1938) have also compared the intervals between successive dart streamers with the intervals between successive strokes that occur in a "normal" discharge and conclude that they are of the same order; from this comparison it is said that "the slowness of the leader process thus causes the type β_2 first stroke to embody in one stroke what would otherwise be two or more strokes from the cloud to ground", and, as a consequence, it would be expected that "type β_2 discharges would not be followed by many subsequent strokes" (Schonland et al., 1938, p. 464). It is argued that this comment is supported by the fact that, among the four cases reported in their work, three had no subsequent strokes while the fourth case presented only one.

The analysis of the fast electric field data of each RL presented in the previous section seem to support comment (i) presented by Schonland et al. (1938), as the microsecond-scale pulses seem to be related to their inception inside the cloud. This observational result added to the similarity between these pulses and those found in K changes of cloud and ground flashes (Krider et al., 1975; Bils et al., 1988; Thottappillil et al., 1990; Rakov et al., 1992) suggest that the nature and origin of the dart streamers can be explained and described within the bidirectional leader concept (first presented by Kasemir, 1950, 1960, and recently summarized by

Mazur, 2002). As the terminology adopted throughout section 3 of this presented paper suggests, we believe that the type β_2 negative leaders are the visible manifestation of the development of RLs that are initiated inside the cloud, connect to the upper positive leader channel and propagate below the cloud-base during the development of a bipolar, bidirectional leader that precedes a lightning flash to ground.

We propose that after one or more RLs are initiated (through processes that still remain open) they propagate throughout previously ionized channels produced by the in-cloud positive portion of the bidirectional leader. As in the cases of RLs observed by Saba et al. (2008), they move in a retrograde fashion, i.e., towards the origin of the flash. Some of these RLs can connect to one of the active branches of the positive leader, which induces the inception of a luminous process that also propagates towards the origin of the flash, similarly to what has been reported by Mazur and Ruhnke (2011) as M components in upward positive leaders. When this luminous process is intense enough it can penetrate the negative downward portion of the bidirectional leader, eventually reaching the region below the thundercloud and moving towards the tip of the negative portion that has been ionized during the stepped leader phases. The intense return pulse of luminosity that optically appears as the dart streamer reported by Schonland et al. (1938) and that could be observed in our high-speed video recordings is the final stages of luminous process initiated by a RL. This hypothesis is illustrated by Figure 5: (a) the bidirectional leader has started to ionize an upward and horizontal positive channel inside the cloud and a downward negative channel that moves towards the ground; (b) recoil leaders are initiated in inactive branches of the positive portion of the channel, propagating downward towards the origin of the discharge; (c) after the recoil leaders connect with an active branch of the positive leader they eventually cross the origin and penetrate the negative portion of the bidirectional leader, catching up with the lower tip and producing the luminosity pulse observed with the help of the high-speed camera; and (d) once the recoil leader propagation is finished both portions of the bidirectional leader continue to propagate, ionizing the lightning channel until the negative leader touch the ground and the return stroke occur.

We believe that the physical process that we propose in this paper is coherent with the current status of the bidirectional leader model of lightning formation (Mazur, 2002), in which M components and dart leaders are recoil leaders inserted on different situations or regimes (Mazur and Ruhnke, 2011). The main observational evidences for our hypothesis are discussed in detail section 3.3, above.

Finally, concerning the speculative comment (ii) presented by Schonland et al. (1938), we believe that Case 1 of the present paper, as mentioned on section 3.3, is an evidence that return strokes initiated by a type β_2 leader can be followed by a relatively large number of subsequent strokes, especially if one compares it to the average number of strokes per flash (video multiplicity) that can be found in recent lightning literature (Saba et al., 2006; Saraiva et al., 2010). Additionally, the particularly high number of recoil leaders observed by Saba et al. (2008, and auxiliary materials) during the development of positive leaders to ground indicate that such process might not responsible for a neutralization of electric charges comparable to that of a subsequent return stroke. It is also worth mentioning that, as discussed on section 3.3, above, it is not possible to infer if there is any effect over the estimated peak current value of a return stroke initiated by a type β_2 leader based on the three cases that were detected.

4. SUMMARY AND CONCLUDING REMARKS

For the first time since the seminal photographic studies of Schonland et al. (1938) we were able to record and identify seven cases of type β_2 leaders in negative cloud-to-ground flashes. It was possible to estimate their propagation speed, allowing us to compare them to other types of leader processes in lightning, and also correlate their optical characteristics with electric field changes measured by a fast antenna. From this analysis we concluded that the stepped leader phases of a type β_2 leader is very similar to what one would consider a “regular” stepped leader, while the “dart streamer” (using the terminology initially presented by Schonland et al., 1938) presents a remarkable similarity to dart and recoil leaders in terms of both optical signatures and propagation speeds. In the three cases for which electric field data were available it was possible to associate the inception of each dart streamer to a sequence of microsecond-scale pulses that are remarkably similar to some variations observed in K changes of cloud and ground flashes. Given these similarities, we have proposed a hypothesis concerning the nature of the dart streamers in the context of the bidirectional leader concept. We suggest that recoil leaders initiated near the positive portion of the bidirectional leader channel can attach to one of its branches and then propagate downward towards the leader origin, cross it, and move throughout the negative portion of the channel, reaching its tip and appearing as the “dart streamer” observed in high-speed video recordings of type β_2 leaders.

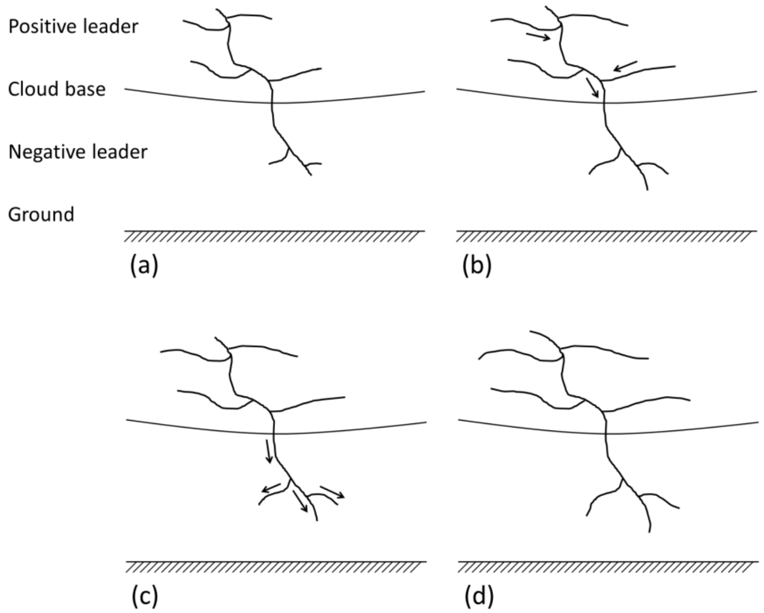

Figure 5. Representation of the hypothesis presented in this work, which consists in considering that the dart streamers observed optically in type β_2 leader are, in fact, manifestations of recoil leaders initiated inside the cloud in the positive end of the bidirectional lightning leader (b) and that reach the tip of the still downward developing negative end (c). The arrows represent the occurrence recoil leaders and their direction of propagation.

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