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Geophysical Research Letters

RESEARCH LETTER
10.1029/2024GL110492

The Role of Secondary Recoil Leaders in the Formation of Subsequent Return Strokes

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Key Points:
- Use of high-speed cameras to study recoil leaders in upward lightning flashes
- Secondary recoil leaders boost the development of previous recoil leaders
- Secondary recoil leaders likely influence the development of dart leaders/subsequent return strokes

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Citation:
Cruz, I. T., Saba, M. M. F., Silva, J. C. O., & Schumann, C. (2025). The role of secondary recoil leaders in the formation of subsequent return strokes. *Geophysical Research Letters*, *52*, e2024GL110492. https://doi.org/10.1029/2024GL110492

Received 30 MAY 2024
Accepted 4 OCT 2024

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Abstract

Recoil leaders develop in lightning flash decayed channels. The propagation of a recoil leader depends on the charges stored at its tip and the conductivity of the decayed channel. When the recoil leader propagates over the entire channel, a subsequent return stroke happens. Recoil leaders very often cease propagating before they reach the ground, that is, only part of the decayed channel is reionized. The present work aims to analyze the herein named secondary recoil leader that connect with the primary recoil leaders and cause them to start propagating again. We believe that the secondary recoil leader injects additional charge into the primary recoil leader, allowing the recoil leader reionize the whole decayed channel of the lightning flash. High-speed videos analysis of upward lightning flashes shows that secondary recoil leaders play an important role on the formation and progression of dart leaders/subsequent return strokes.

Plain Language Summary

The recoil leader is a phenomenon that occurs in all types of lightning flashes (upward, downward and intracloud flashes). They arise in the remnants of decayed channels of positive leaders, partially or completely rebuilding these channels. The recoil leaders are responsible for some physical processes observed in lightning flashes. Thus, understanding how these physical processes originate is of significant importance. This work presents the role of secondary recoil leaders (recoil leaders that connect to preexisting recoil leaders) in the integral reconstruction of the decayed channels of the analyzed lightning flashes.

1. Introduction

Upward lightning occurs when a leader discharge (usually positive) starts from tall structures and propagates toward the cloud base forming an illuminated and ionized channel. The channel formed by the positive leader decays after a few tens of milliseconds (Heidler et al., 2013; Mazur & Ruhnke, 2011; Saba et al., 2015, 2016; Schumann et al., 2019; Warner, 2012). During the decaying process in a branched positive leader channel, a portion in the remnants of the channel may reionize and return to a good conductive state, resembling a floating conductor (Mazur et al., 2013). Due to the ambient electric field, opposite charges accumulate at the ends of such floating conductor, making it to propagate on both directions, stretching along the decayed channel. The negative end propagates toward the branching point at the main channel of the upward positive leader, while the positive end propagates toward the open end of the branched leader channel, possibly to non-ionized air. In the scientific community there are variations on the terminology used to describe this bidirectional and bipolar discharge (Jensen et al., 2021). However, until the community reaches a new consensus, in this work we will classify these bidirectional and bipolar discharges as recoil leader (Mazur, 2016; Mazur & Ruhnke, 1993, 2011; Mazur et al., 2013; Saba et al., 2008; Wang et al., 2019; Warner, 2012).

With the development of recoil leaders, some physical processes can happen in lightning flashes. A recoil leader that propagates across the entire channel of the upward positive leader can generate initial continuous current (ICC) pulses, dart leaders/subsequent return strokes and M components. Meanwhile, recoil leaders who cease their development produce attempt leaders (Lu et al., 2008; Saba et al., 2016; Shao et al., 1995). These physical processes not only depend on the stored charge at its ends, but also on the conductivity of the decayed channel, where they are traveling, see Kitagawa et al. (1962), Rakov and Uman (1990), and Ferro et al. (2012). Thus, the higher the charge in the recoil leader and the more conductive the upward lightning channel, the more easily the recoil leader will propagate along the channel.

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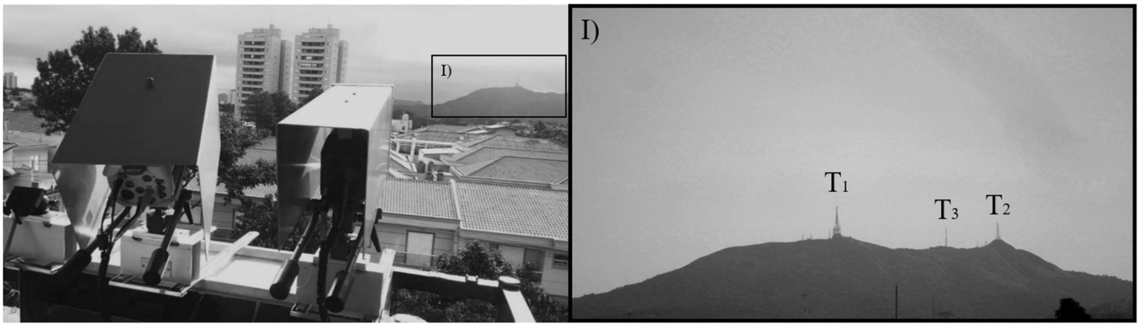

Figure 1. The image on the left shows the high-speed cameras setup. The image on the right shows three telecommunications towers (T_1, T_2, and T_3) on the top of the Jaraguá Peak (Brazil).

With the aid of two high-speed cameras (Phantom v310 and v711), the present work investigates the occurrence of recoil leader in an upward lightning flash (UP 154) and a bipolar upward flash (UP 44), both originated on a telecommunication tower on top of Jaraguá Peak, Brazil. The videos show secondary recoil leaders connections with the positive end of previous recoil leaders.

2. Instrumentation

Jaraguá Peak is the highest point in the city of Sao Paulo, Brazil, standing at approximately 1,100 m above sea level. On the peak, there are telecommunications towers (tall structures) that, combined with the elevation of the peak, create favorable conditions for the formation of upward lightning flashes. These upward lightning flashes are initiated when the electric field over tall structures intensifies. At Jaraguá Peak, this process is triggered by nearby flash activity (Cruz et al., 2022; Saba et al., 2016; Schumann et al., 2019).

2.1. High-Speed Cameras

The high-speed cameras equipped with a 6.5 mm lens were installed at a distance of 5 km from the Jaraguá Peak (Figure 1). The bipolar upward lightning flash (UP 44) was filmed by high-speed camera Phantom v310 on 1 February 2013, at 19:58:41 UTC (Universal Time Coordinated). The camera was configured to acquire 10,000 fps, with an exposure time of 98.75 μs and with image spatial resolution of 640 × 480 pixels (Cruz et al., 2022). The upward lightning flash (UP 154) was filmed by a Phantom v711 camera on 24 November 2018, at 21:20:29 UTC. The camera was configured to film lightning flashes with a frame rate of 37,819 fps, with an exposure time of 25.84 μs and with image spatial resolution of 368 × 416 pixels. For more information on the operation of the used high-speed cameras, see Saba et al. (2006), Warner et al. (2013), Saba et al. (2016), and Schumann et al. (2019).

2.2. Lightning Location Systems

Data from Earth Networks Total Lightning Network (ENTLN), see Liu and Heckman (2012), Marchand et al. (2019), and Zhu et al. (2022), were used to identify the polarity and estimate the peak current of the positive cloud-ground (+CG) lightning flash that triggered the upward lightning flashes (UP 44 and UP 154).

3. Data

3.1. Flashes Description

Both upward lightning flashes (UP 44 and UP 154) had positive upward leaders initiated at the highest telecommunication tower of the Jaraguá Peak (T_1—130 m). The initiation of the upward leaders in both flashes was triggered by nearby +CG flashes; a common feature in this region, as evidenced by the analysis of numerous upward flashes conducted by Schumann et al. (2019). The occurrence of recoil leaders along the upward leader development (observed only on positive leaders; see for example the works of Mazur (2002), Saba et al. (2008), Heidler et al. (2015), and Cruz et al. (2022)) confirmed the positive polarity of the upward leaders of both lightning flashes.

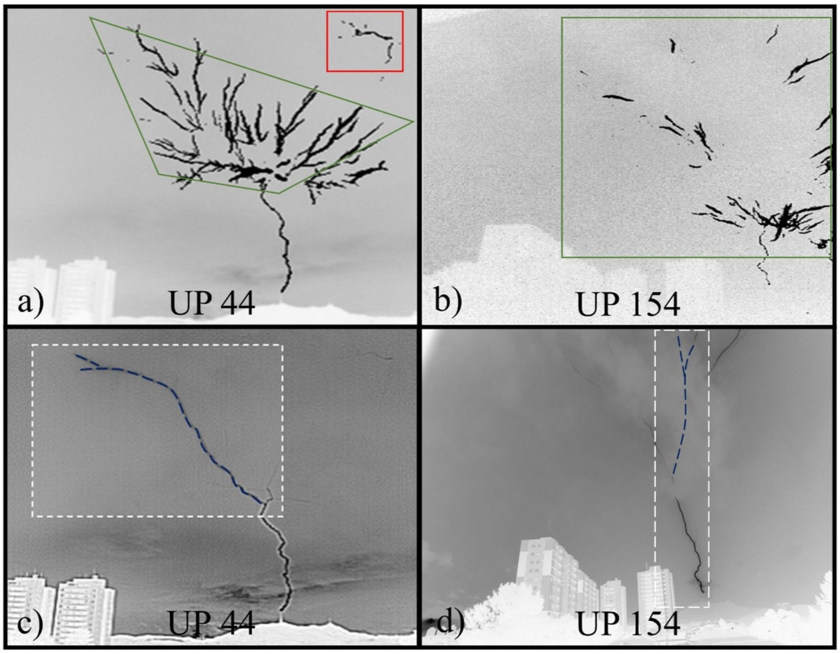

Figure 2. Images (a and b) were built from stacked frames, from which it is possible to see many recoil leaders developing through the upward positive leader branches. The UP 44 stack was constructed from 1,069 frames in an interval of 117 ms and the UP 154 stack was constructed from 3,579 frames in an interval of 202 ms. Some frames saturated the images, so they were disregarded. Two processes are highlighted in (a): (1) inside the green line, several recoil leaders were registered during the development of the positive upward leader; (2) inside the red rectangle, the development of an intracloud flash. Images (c and d) are photos of the UP 44 and UP 154 lightning flashes, respectively. The blue dashed lines were used to improve the visualization of the recoil leader development regions analyzed in this research; the white dashed frames indicate the areas shown in Figures 3 and 4. In image (c) the brightness of the channel was dim and in image (d) there is a cloud that prevents part of the channel from being seen. Images (b and d) are different because image (b) was a record taken by a high-speed camera with a 6 mm lens and image (d) was taken by a Nikon D800 still camera with a 20 mm lens. The images were inverted, and contrast enhanced to facilitate viewing.

The first case analyzed, UP 44, occurred in 2013 (Figures 2a and 2c). The event began with an upward positive leader at 19:58:41.978 UT, just 10 ms after a +CG return stroke occurred 21 km away, with a peak current of 43 kA as detected by ENTLN (see video UP44allskyview.mp4 in Data Availability Statement).

As the upward positive leader of UP 44 propagated upwards, it exhibited numerous branches and recoil leaders that developed toward the tip of the tower along the main channel of the upward lightning flash. 121 ms after the beginning of the upward positive leader of lightning UP 44, it was possible to observe an intracloud lightning (IC flash) developing near the cloud base. 48 ms after the IC flash appeared, a recoil leader emerged in the decaying channel of the UP 44 and connected with the IC flash. After the connection, the positive leader traveled along the decaying channel of the UP 44 and struck the tower, producing a subsequent positive return stroke. See the details of this peculiar flash in the work of Cruz et al. (2022). In total, UP 44 lasted 555 ms.

The second case analyzed (UP 154) occurred in 2018 (Figures 2b and 2d). The event began with an upward positive leader from the same tower as UP 44 at 02:17:14.903 UT, just 3 ms after a +CG return stroke occurred 15 km away, with a peak current of 36 kA as detected by ENTLN. The triggering of the upward leader occurred during the continuing current (CC) that followed the +CG (see the video UP 154.cine presented in Data Availability Statement, in $t = 60{,}263.17$ μs). As the upward positive leader of the UP 154 propagated upwards it exhibited numerous branches and recoil leaders that developed along the main channel toward the tower. In total, UP 154 lasted 409 ms.

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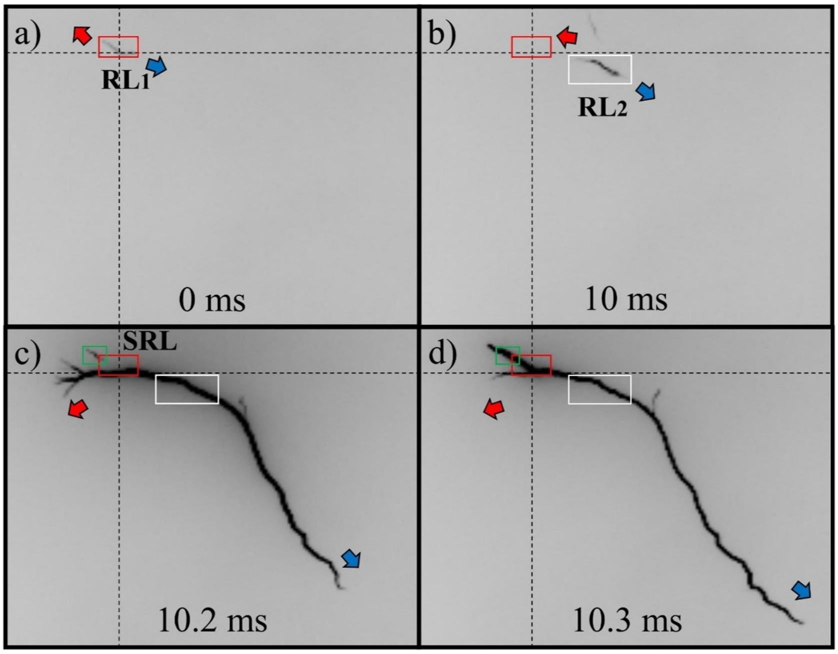

Figure 3. Recoil leaders RL_1 and RL_2 and secondary recoil leader SRL (UP 44). The direction of propagation of the positive ends of the recoil leaders is represented by red arrows and the negative ends by blue arrows. The crossing of horizontal and vertical dotted lines is a reference to make the image easier to analyze. The section viewed in this image is represented in Figure 2c by the dashed white rectangle.

4. Analysis

4.1. Connection of Secondary Recoil Leader With Preexistent Recoil Leader

Figures 3a and 3b show the development of two recoil leaders (RL_1 and RL_2) and the origin of a secondary recoil leader (SRL) in Figure 3c, in the region delimited by the green rectangle.

The RL_1 first appears at $T = 0$ in the image sequence in Figure 3 (t = 24,899.90 μs in the video UP 44.cine presented in Data Availability Statement). The red rectangle shows the region of its origin (Figure 3a). It develops through the decayed channel of the upward positive leader. RL_1 is shown in Figure 3 only to highlight the region of origin of the secondary recoil leader (Figure 3c). After 10 ms, another recoil leader (RL_2—white rectangle) appears a little below the region of origin of the RL_1 (Figure 3b). Figure 3c, shows (0.2 ms later) the development of the RL_2 and the origin of the secondary recoil leader (green square). Note that this secondary recoil leader originates in the decayed channel of the positive end of the RL_1 (top left corner of the red rectangle in Figure 3a). Finally, in Figure 3d, the secondary recoil leader connects to the RL_2.

From the sequence shown in Figure 3 and from similar cases, we define as secondary recoil leaders recoil leaders that start while a previously initiated recoil leader is still growing and then connects with the primary recoil leader.

During the development of UP 44 and UP 154 lightning flashes, the presence of secondary recoil leader close to the preexistent recoil leader could be seen. Most of the secondary recoil leader originated from decaying upward positive leader channels. However, there were also cases of secondary recoil leader that had their origin in the decayed positive end of previous recoil leader.

4.2. Influence of Secondary Recoil Leaders on the Development of Dart Leaders

Upward lightning flash UP 154 had an extraordinary number of subsequent return strokes (27). In one of these subsequent strokes a secondary recoil leader connecting to a recoil leader was observed. To show the influence of the connections between secondary recoil leader and recoil leader, the propagation of the dart leader that originated the first subsequent return stroke of UP 154 lightning flash was analyzed.

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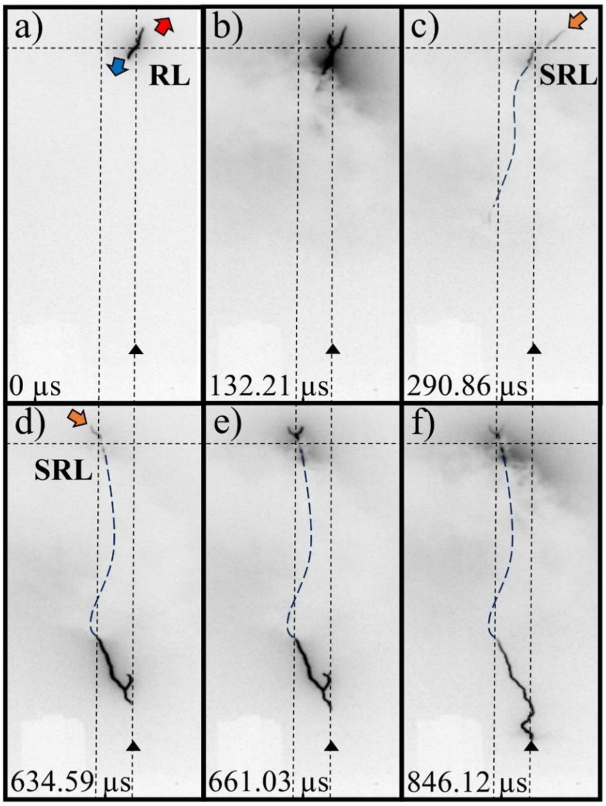

Figure 4. Development of a dart leader/subsequent return stroke with connections from two secondary recoil leaders (UP 154). The black triangles represent the tip of tower T_1 at the Jaraguá Peak. The visualization of part of the development of the recoil leader was blocked by a cloud (which is reconstructed from other frames and represented by the blue dashed line). The section analyzed in this image is represented in Figure 2d inside the dashed white rectangle.

The recoil leader first appears at $T = 0$ in the image sequence in Figure 4 (t = 290,670.32 µs in the video UP 154.cine presented in Data Availability Statement). The orange arrows indicate secondary recoil leader connections with recoil leader (Figures 4c and 4d). After these connections, it is possible to see the intensification of the luminosity in the recoil leader channel, as the connections made by these secondary recoil leaders (Figures 4d and 4e) injects additional charge into the previous recoil leader, enabling them to reionize the whole decayed channel of the negative upward lightning and finally producing the return stroke (Figure 4f).

5. Discussion and Conclusion

In the analyses of the upward lightning flashes UP 44 and UP 154, the formation of floating portions of ionized channels connecting to previous recoil leader were observed, the same "floating channels" as observed by Wu et al. (2019). Wu et al. (2019) were unable to characterize the floating channels that emerged in their work, suggesting that these channels could be bidirectional and bipolar leaders, space leaders or recoil leader. In the present work, such floating channels appeared in decayed parts of positive leaders (positive end of recoil leader, Figure 3c, or in decayed channels of the upward positive leaders). As they developed into decayed branches of positive leaders and connected to previous recoil leader, they have been here denominated as secondary recoil leaders. The explanation for the floating channels observed by Wu et al. (2019) as possibly being a recoil leader that emerged in an upward positive leader channel not detected by optical instruments is the most acceptable and agrees with the observations presented in this research.

In addition to characterizing the secondary recoil leader appearing near the ends of recoil leader, the current research also showed the influences of their connections with recoil leader. According to Shao et al. (1995) the recoil leader may decay before reaching the ground, producing attempt leader. This feature shows the importance of secondary recoil leader in the development of the dart leader/subsequent return stroke. We believe that the secondary recoil leader injects additional charge into the primary recoil leader. They allow the previous recoil leader to develop toward the initiation point of the upward lightning flash, generating a dart leader/subsequent return stroke. In Figure 4c the luminosity of the recoil leader channel would be much attenuated if no secondary recoil leader had happened there; it could have decayed and formed an attempt leader.

Out of 27 return strokes of UP 154 lightning, secondary recoil leaders could be observed in five return strokes (1st, 2nd, 4th, 5th, and 7th). It was observed that the secondary recoil leaders are more frequent during the first return strokes, when the channel is poorly ionized. As subsequent return strokes occur, the lightning channel becomes more conducting and secondary recoil leader are not required for recoil leader to fully propagate through the channel.

The subsequent positive return stroke of the UP 44 bipolar upward lightning flash was produced by the connection of a recoil leader with an intracloud flash, see Cruz et al. (2022). During recoil leader propagation toward intracloud flash, secondary recoil leader connections were observed with the previous recoil leader. If there were no secondary recoil leader, possibly the recoil leader would not connect to the intracloud lightning and there would not have a positive return stroke.

Therefore, this work shows that when recoil leader does not reionize the entire decay lightning channel, secondary recoil leaders are needed to boost their development and give rise to dart leaders/subsequent return strokes. In a similar manner, secondary recoil leader may be important for the origin of M components and ICC pulses.

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Acknowledgments

This research has been supported by the Coordination of Superior Level Staff Improvement—CAPES (Project 88887.676681/2022-00), by National Council for Scientific and Technological Development—CNPq (Projects 130928/2020-8; 167552/2022-8) and by São Paulo Research Foundation—FAPESP (Projects 2012/15375-7; 2013/05784-0; 2022/10808-4; 2023/03908-5; 2023/15336-6). This work is supported in part by the National Research Foundation of South Africa (CSRP23030380658). The authors would like to thank Lie Liong Bee (Benny), Raphael B. Guedes da Silva and Guilherme Aminger, for their assistance in obtaining the high-speed images and technical support with the equipment, and to Jeff Lapierre for sharing ENTLN data.

Data Availability Statement

The high-speed videos (UP 44 and UP 154) analyzed in this work are available in Cruz (2024).

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