The role of secondary recoil leaders in the formation of subsequent return strokes

Ivan Toucedo Cruz[1], Marcelo Magalhães Fares Saba[2], José Cláudio Oliveira Silva[3], and Carina Schumann[4]

[1]National Institute for Space Research, INPE
[2]INPE - National Institute for Space Research
[3]APTEMC
[4]University of the Witwatersrand

June 10, 2024

Abstract

Recoil leaders develop in lightning flash decayed channels. The propagation of a recoil leader depends on its intensity and on the conductivity of the decayed channel. When the recoil leader is strong enough to propagate over the entire channel, a subsequent return stroke happens. When the recoil leader is not intense enough, only a partial reconstruction of the channel occurs, that is, only part of the decayed channel is reionized. The present work aims to analyze the herein named secondary recoil leader that originates near a previously formed recoil leader. When these secondary recoil leaders develop and connect to previous recoil leaders, they provide enough energy for the recoil leader to 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.

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[2]Johannesburg Lightning Research Laboratory, School of Electrical and Information Engineering, University of the Witwatersrand, South Africa.

Corresponding author: Ivan T. Cruz (ivan.cruz@inpe.br)

Key Points:

- Observation of secondary recoil leaders.
- Secondary recoil leaders boosting the development of previous recoil leaders.
- Influence of secondary recoil leaders on the development of dart leaders/subsequent return strokes.

Abstract

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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 most of the 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 towards the cloud base forming an illuminated and ionized channel. The channel formed by the positive leader decays after a few tens of milliseconds (Mazur & Ruhnke, 2011;

Warner, 2012; Heidler et al., 2013; Saba et al., 2015; Saba et al., 2016; Schumann et al., 2019). 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 towards the branching point at the main channel of the upward positive leader, while the positive end propagates towards the open end of the branched leader channel, possibly to non-ionized air. This bidirectional and bipolar discharge is called recoil leader – RL (Mazur & Ruhnke, 1993; Saba et al., 2008; Mazur & Ruhnke, 2011; Warner, 2012; Mazur et al., 2013; Mazur, 2016; Wang et al., 2019).

With the development of RL, some physical processes can happen in lightning flashes. RL with enough intensity to propagate 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, RL low on intensity will develop attempt leaders (Shao et al., 1995; Lu et al., 2008; Saba et al., 2016). These physical processes not only depend on the intensity of the RL, that is, 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 & Uman, (1990) and Ferro et al., (2012). Thus, the higher the charge in the RL and the more conductive the upward lightning channel, the more easily the RL will propagate along the channel.

With the aid of two high-speed cameras (Phantom v310 and v711), the present work investigates the occurrence of RL 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 (SRL) connections with the positive end of previous RL.

2 Instrumentation

The Jaraguá peak is the highest place in the city of Sao Paulo (Brazil), with approximately 1,100 m above sea level. On it, there are telecommunications towers that, combined with the peak itself, intensify the electric field in the region, are conducive to the development of upward lightning flash (Saba et al., 2016; Schumann et al., 2019; Cruz et al., 2022).

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 February 1, 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 640x480 pixels (Cruz et al., 2022). The upward lightning flash (UP 154) was filmed by a Phantom v711 camera on November 24, 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 368x416 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), Schumann et al. (2019).

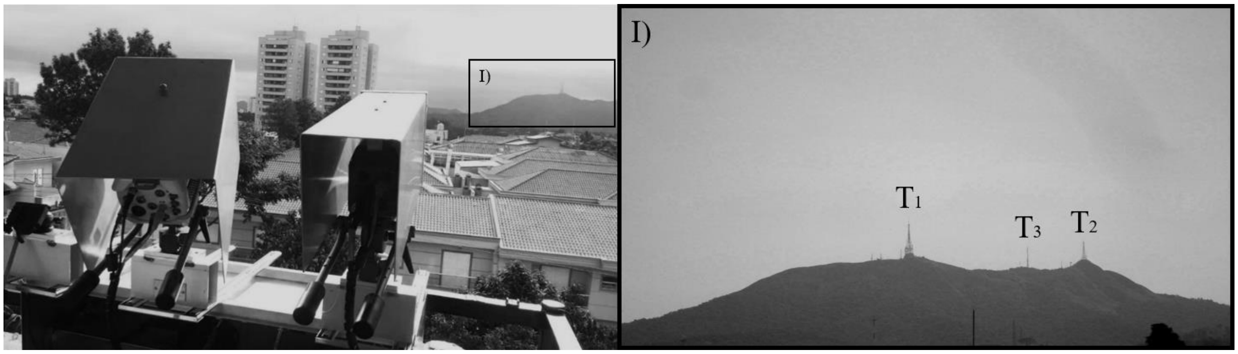

Figure 1. The image on the left shows the high-speed cameras setup. The image on the right shows three telecommunications towers (T_1, T_2 and T_3) on the top of the Jaraguá peak (Brazil).

2.2 Lightning location systems

Data from Earth Networks Lightning (ENL), see Liu & 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

The lightning flashes UP 44 and UP 154 were triggered by +CGs that were located at 21 and 15 km away from the tower and had an estimated peak current of 43 and 36 kA, respectively. The occurrence of RL along the upward leader development (present only on positive leaders; see for example the works of Mazur (2002); Saba et al., (2008) and Heidler et al., (2015) and Cruz et al., (2022)) confirmed the positive polarity of the upward leaders of both lightning flashes.

The UP 44 bipolar upward lightning flash had an upward leader that transferred negative charges to the ground, followed by a positive subsequent return stroke. The positive return stroke was originated by the connection of a RL with an intracloud lightning, see Cruz et al. (2022). The UP 44 initiation was triggered by a negative leader propagating during the continuing current of the +CG return stroke, and the UP 154 initiation was triggered right after the occurrence of the +CG return stroke. Both upward positive leaders (UP 44 and UP 154) initiated at the highest telecommunication tower of the Jaraguá peak (T_1 – 130 m). The positive leaders developed toward the cloud base, branching along the way (Figure 2). When the upward positive leaders started to decay, RL emerged over the branches, as shown next.

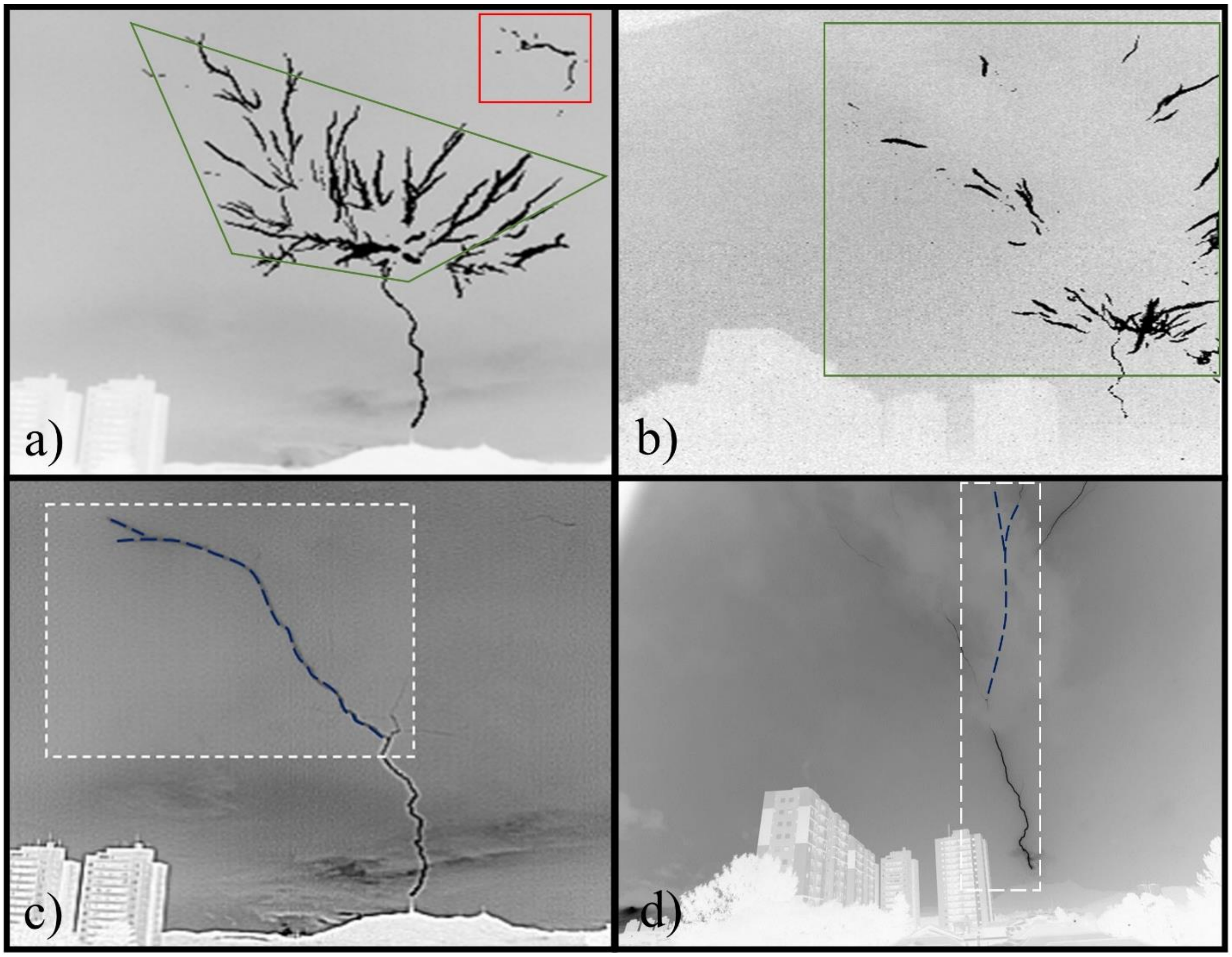

Figure 2. Image a) and b) were built from the stack of a large number of frames from which it is possible to see many RL developing through the upward positive leader branches (Figure 2a – UP 44 and Figure 2b – UP 154). Two processes are highlighted: (1) inside the green line, several RL registered during 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, respectively. The blue dashed lines were used to improve the visualization of the RL development regions analyzed by this research and 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 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.

4 Analysis

4.1 Connection of secondary recoil leader (SRL) with preexistent recoil leader

During the development of the UP 44 and UP 154 lightning flashes, the presence of SRL close to the preexistent RL could be seen. Most of the SRL originated from decaying upward positive leader channels. However, there were also cases of SRL that had their origin in the decayed positive end of previous RL. An example is given in the image sequence shown in Figure 3. Figures 3a and 3b show the development of two recoil leaders (RL_1 and RL_2) with the origin of a SRL (Figure 3c – 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 Open Research). 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 SRL (Figure 3c). In Figure 3b, after 10 ms, another recoil leader (RL_2 – white rectangle) appears a little below the region of origin of the RL_1. Figure 3c, shows the development of the RL_2 (200 µs after its start) and the origin of the SRL (green square). Note that this SRL 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 SRL connects to the RL_2.

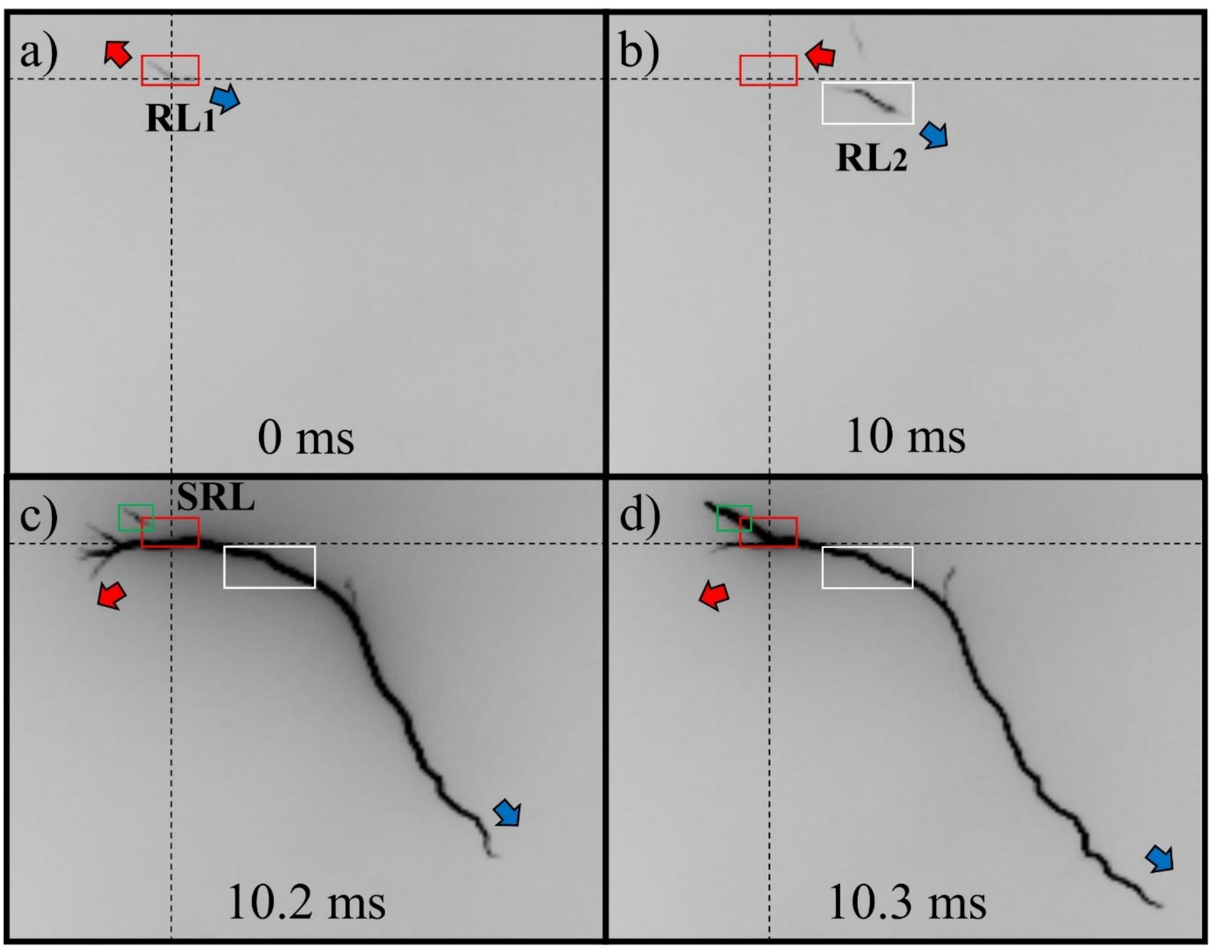

Figure 3. RL_1, RL_2 and SRL (UP 44). The direction of propagation of the positive ends of the RL is represented by red arrows and the negative ends by blue arrows. The crossing of horizontal and vertical dotted lines is a reference to make the image easier to view. The section analyzed in this image is represented in figure 2c by the blue dashed lines inside the dashed white rectangle.

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 SRL connecting to a RL was observed. To show the influence of the connections between SRL and RL, the propagation of the dart leader that originated the first subsequent return stroke of UP 154 lightning flash was analyzed. The RL 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 Open Research). The orange arrows indicate SRL connections with RL (Figures 4c and 4d). After these connections, it is possible to see the intensification of the luminosity in the RL channel, as the connections made by these SRL (Figures 4d and 4e) energize the previous RL, enabling them to reionize the whole decayed channel of the negative upward lightning and finally producing the return stroke (Figure 4f).

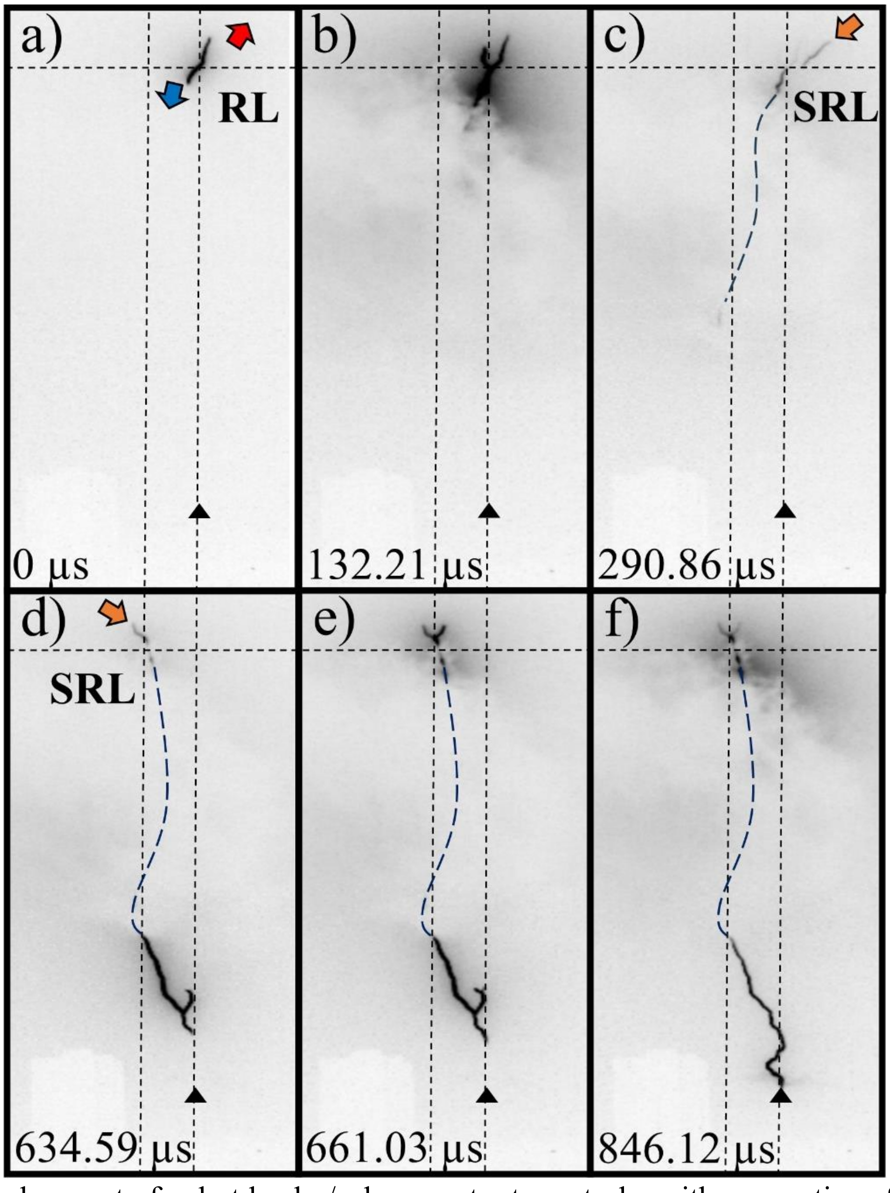

Figure 4. Development of a dart leader/subsequent return stroke with connections from two SRL (UP 154). The black triangles in the images represent the tip of tower T_1 at the Jaraguá peak. The visualization of part of the development of the RL was blocked by a cloud (which is reconstructed from other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

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 RL 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 RL. In the present work, such floating channels appeared in decayed parts of positive leaders (positive end of RL, Figure 3c, or in decayed channels of the upward positive leaders). As they developed into decayed branches of positive leaders and connected to previous RL, they have been here denominated as secondary recoil leaders (SRL). The explanation for the floating channels observed by Wu et al. 2019 as possibly being a RL 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 SRL appearing near the ends of RL, the current research also showed the influences of their connections with RL. According to Shao et al. (1995) the RL may decay before reaching the ground, when they do not have enough intensity to reionize the lightning flash channel. This feature shows the importance of SRL in the development of the dart leader/subsequent return stroke. They give energy to the RL to reionize the decayed channel of the negative upward lightning. They allow the previous RL 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 RL channel would be much attenuated if no SRL had happened there; it could have decayed and formed an attempt leader.

Out of 27 return strokes of UP 154 lightning, SRL could be observed in five return strokes (1st, 2nd, 4th, 5th and 7th). It was observed that the SRL are more frequent during the first return strokes, when the channel is poorly ionized. As subsequent return strokes occur, the lightning channel becomes more consolidated and SRL are not required for RL 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 an RL with an intracloud flash, see Cruz et al. (2022). During RL propagation towards intracloud flash, SRL connections were observed with the previous RL. If there were no SRL, possibly the RL would not connect to the intracloud lightning and there would not have a positive return stroke.

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

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 (Unique Grant No.: 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 ENL data.

Open Research

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

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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 February 1, 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 640x480 pixels (Cruz et al., 2022). The upward lightning flash (UP 154) was filmed by a Phantom v711 camera on November 24, 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 368x416 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), Schumann et al. (2019).

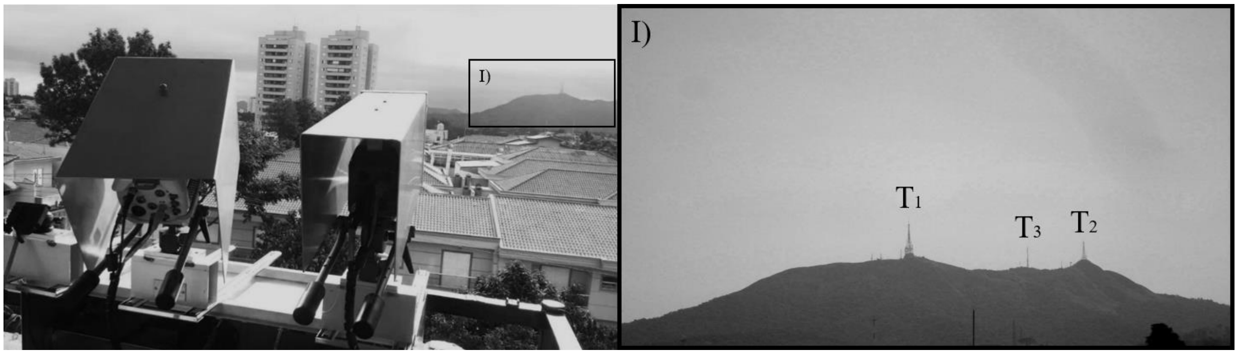

Figure 1. The image on the left shows the high-speed cameras setup. The image on the right shows three telecommunications towers (T_1, T_2 and T_3) on the top of the Jaraguá peak (Brazil).

2.2 Lightning location systems

Data from Earth Networks Lightning (ENL), see Liu & 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

The lightning flashes UP 44 and UP 154 were triggered by +CGs that were located at 21 and 15 km away from the tower and had an estimated peak current of 43 and 36 kA, respectively. The occurrence of RL along the upward leader development (present only on positive leaders; see for example the works of Mazur (2002); Saba et al., (2008) and Heidler et al., (2015) and Cruz et al., (2022)) confirmed the positive polarity of the upward leaders of both lightning flashes.

The UP 44 bipolar upward lightning flash had an upward leader that transferred negative charges to the ground, followed by a positive subsequent return stroke. The positive return stroke was originated by the connection of a RL with an intracloud lightning, see Cruz et al. (2022). The UP 44 initiation was triggered by a negative leader propagating during the continuing current of the +CG return stroke, and the UP 154 initiation was triggered right after the occurrence of the +CG return stroke. Both upward positive leaders (UP 44 and UP 154) initiated at the highest telecommunication tower of the Jaraguá peak (T_1 – 130 m). The positive leaders developed toward the cloud base, branching along the way (Figure 2). When the upward positive leaders started to decay, RL emerged over the branches, as shown next.

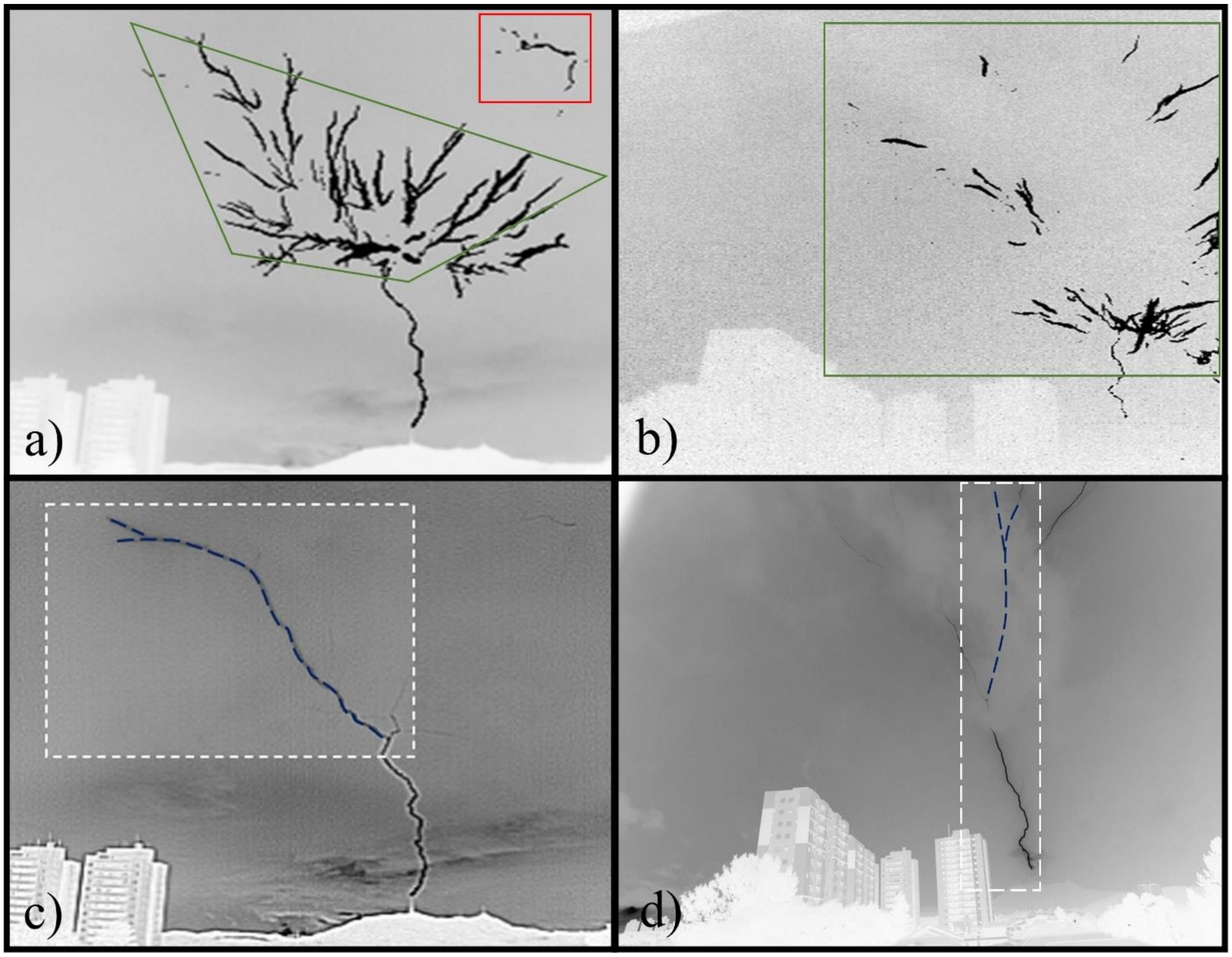

Figure 2. Image a) and b) were built from the stack of a large number of frames from which it is possible to see many RL developing through the upward positive leader branches (Figure 2a – UP 44 and Figure 2b – UP 154). Two processes are highlighted: (1) inside the green line, several RL registered during 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, respectively. The blue dashed lines were used to improve the visualization of the RL development regions analyzed by this research and 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 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.

4 Analysis

4.1 Connection of secondary recoil leader (SRL) with preexistent recoil leader

During the development of the UP 44 and UP 154 lightning flashes, the presence of SRL close to the preexistent RL could be seen. Most of the SRL originated from decaying upward positive leader channels. However, there were also cases of SRL that had their origin in the decayed positive end of previous RL. An example is given in the image sequence shown in Figure 3. Figures 3a and 3b show the development of two recoil leaders (RL_1 and RL_2) with the origin of a SRL (Figure 3c – 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 Open Research). 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 SRL (Figure 3c). In Figure 3b, after 10 ms, another recoil leader (RL_2 – white rectangle) appears a little below the region of origin of the RL_1. Figure 3c, shows the development of the RL_2 (200 µs after its start) and the origin of the SRL (green square). Note that this SRL 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 SRL connects to the RL_2.

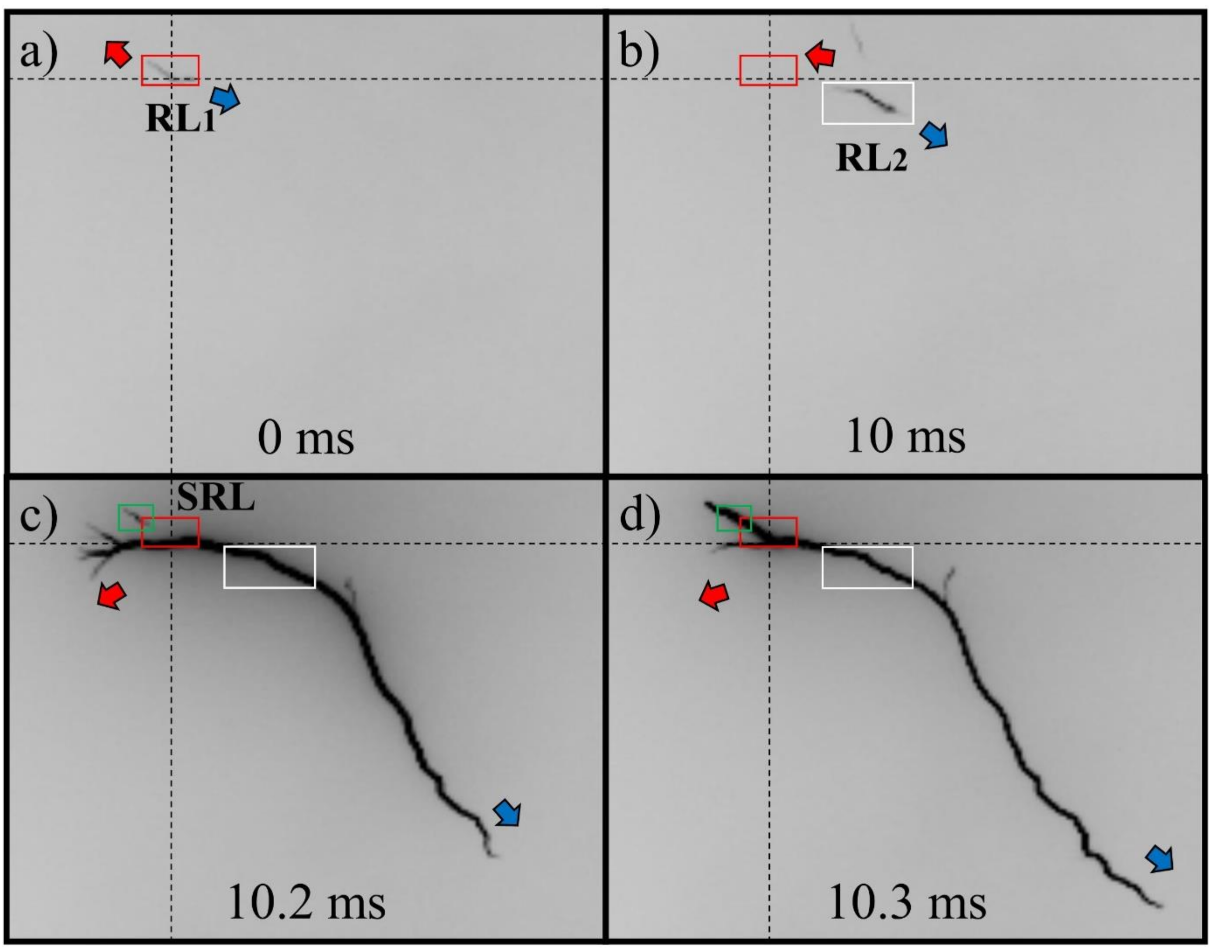

Figure 3. RL_1, RL_2 and SRL (UP 44). The direction of propagation of the positive ends of the RL is represented by red arrows and the negative ends by blue arrows. The crossing of horizontal and vertical dotted lines is a reference to make the image easier to view. The section analyzed in this image is represented in figure 2c by the blue dashed lines inside the dashed white rectangle.

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 SRL connecting to a RL was observed. To show the influence of the connections between SRL and RL, the propagation of the dart leader that originated the first subsequent return stroke of UP 154 lightning flash was analyzed. The RL 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 Open Research). The orange arrows indicate SRL connections with RL (Figures 4c and 4d). After these connections, it is possible to see the intensification of the luminosity in the RL channel, as the connections made by these SRL (Figures 4d and 4e) energize the previous RL, enabling them to reionize the whole decayed channel of the negative upward lightning and finally producing the return stroke (Figure 4f).

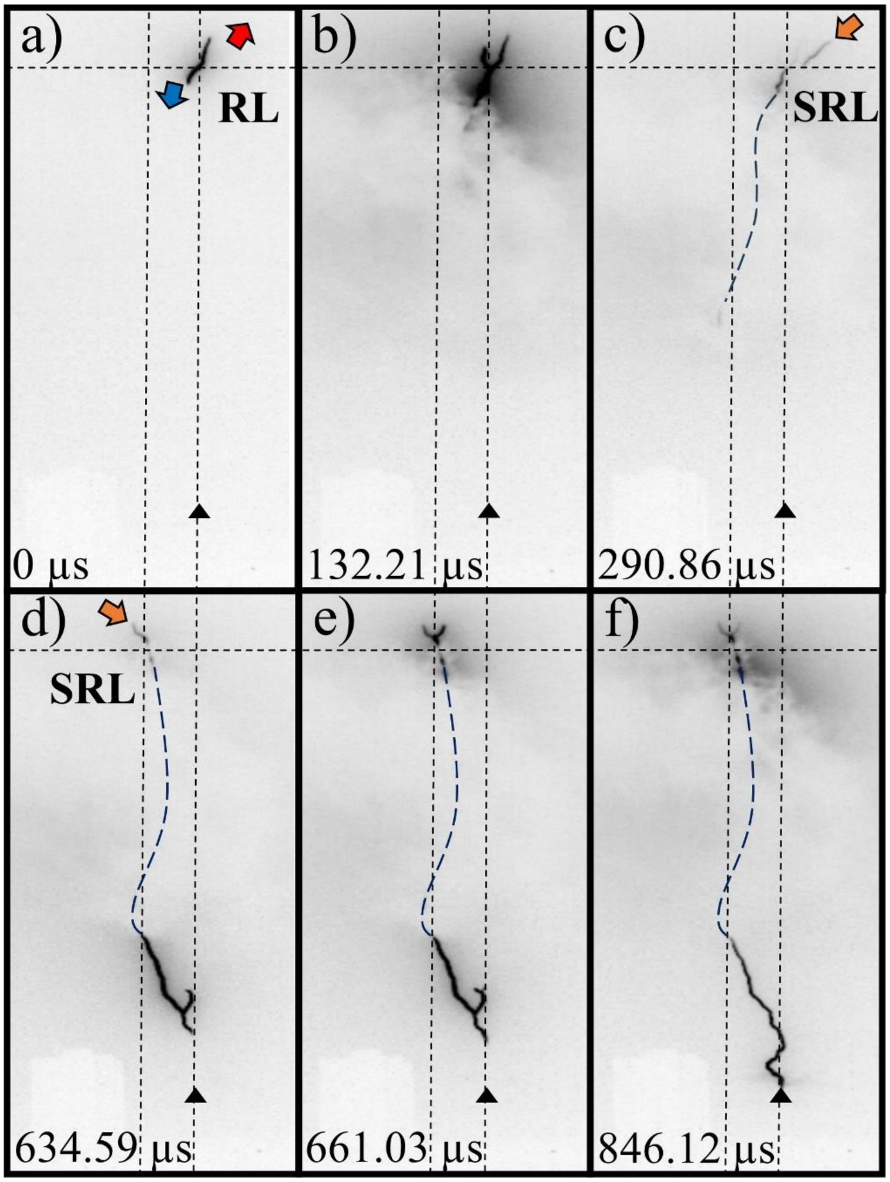

Figure 4. Development of a dart leader/subsequent return stroke with connections from two SRL (UP 154). The black triangles in the images represent the tip of tower T_1 at the Jaraguá peak. The visualization of part of the development of the RL was blocked by a cloud (which is reconstructed from other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

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 RL 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 RL. In the present work, such floating channels appeared in decayed parts of positive leaders (positive end of RL, Figure 3c, or in decayed channels of the upward positive leaders). As they developed into decayed branches of positive leaders and connected to previous RL, they have been here denominated as secondary recoil leaders (SRL). The explanation for the floating channels observed by Wu et al. 2019 as possibly being a RL 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 SRL appearing near the ends of RL, the current research also showed the influences of their connections with RL. According to Shao et al. (1995) the RL may decay before reaching the ground, when they do not have enough intensity to reionize the lightning flash channel. This feature shows the importance of SRL in the development of the dart leader/subsequent return stroke. They give energy to the RL to reionize the decayed channel of the negative upward lightning. They allow the previous RL 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 RL channel would be much attenuated if no SRL had happened there; it could have decayed and formed an attempt leader.

Out of 27 return strokes of UP 154 lightning, SRL could be observed in five return strokes (1st, 2nd, 4th, 5th and 7th). It was observed that the SRL are more frequent during the first return strokes, when the channel is poorly ionized. As subsequent return strokes occur, the lightning channel becomes more consolidated and SRL are not required for RL 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 an RL with an intracloud flash, see Cruz et al. (2022). During RL propagation towards intracloud flash, SRL connections were observed with the previous RL. If there were no SRL, possibly the RL would not connect to the intracloud lightning and there would not have a positive return stroke.

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

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 (Unique Grant No.: 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 ENL data.

Open Research

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

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