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Close View of the Lightning Attachment Process Unveils the Streamer Zone Fine Structure

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Key Points:

- Very close high-speed video observation of lightning attachment reveals details of corona brush, streamers and space stems
- Streamer zone of upward connecting leader increases in size and develops a more filamentary pattern
- Some space stems display streamers emanating from both ends, forming an embryonic bidirectional space leader

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

A very close high-speed video observation of lightning attachment to a building revealed novel details regarding the leader streamer zone dynamics. Upward leaders propagate in a steady and unbranched manner, displaying a uniformly luminous corona brush. The exception being the upward connecting leader (UCL) just before connection, when its streamer zone increases in size and develops a more filamentary pattern. Downward negative leaders have 3-m long multiple streamers emanating from each negative leader tip. On some occasions, plasma formations known as space stems are seen to form in the location previously occupied by negative streamers. Space stems have luminosities comparable to the main leader channel, but are detached from it by 4 m. Some space stems display streamers of their own, including cases where streamers are emanating from both ends. The space stem formation hampered the propagation of the negative leader that was closest to the UCL.

Plain Language Summary

A serendipitous close observation of a natural lightning flash revealed novel details of the lightning attachment process to residential buildings in highly populated areas. A staggering total of 31 lightning precursor channels (called leaders) were launched from nearby buildings in an attempt to intercept the down coming negative leaders. The upward positive leaders propagate almost in a straight path manner, do not branch, and display a uniformly luminous "corona brush" at their tips. This contrasts with the negative leaders coming down from the cloud, which present substantial branching and have numerous filaments (called streamers) emanating from their tips. The high-speed and high-resolution images obtained also revealed that, in some cases, the negative leaders display a luminous formation that is about 2 m long and is detached from the main channel by about 4 m. These observations consist of one of the rare sightings of these luminous formations known in the peer-reviewed literature as "space stems." It is understood that space stems play a key role in the stepped propagation of negative leaders. In these observations, it seems that they hamper the leader propagation, making the upward connecting leader intercept a different downward branch, which was originally more distant from the striking point.

1. Introduction

The effectiveness of a lightning protection system (LPS) depends on its efficiency to intercept the down coming lightning leader which is usually done by emitting an upward connecting leader (UCL). Detailed characterization of UCLs and of the attachment process is a key step toward quantifying the LPS zone of protection for improving LPS designs. UUL, that is, those events that initiate an upward leader but fail to make contact with the downward leader, are also of great importance in lightning protection. They can cause damage to equipment vulnerable to sparks or induced currents, and may be powerful enough to injure someone.

Although lightning attachment observations have been reported from tall towers (e.g., Saba et al., 2015; Visacro et al., 2017, towers higher than 60 m over mountains), from buildings (Saba et al., 2017), and from small structures (Schoene et al., 2008, vertical conductor of 7 m height), no close and detailed high-speed video observation of the attachment process of UCL from common buildings is presently available in the literature. This study presents observational data of several positive upward leaders competing to connect with negative leaders of a downward cloud-to-ground flash that struck a residential building. Furthermore, the use of high-resolution and high-speed video images reveals details of the electrical discharge development around the leader tip and the formation of several streamers and space stems ahead of the advancing negative leader.

Leader channels in negative cloud-to-ground flashes propagate in a stepped manner, with the overall dynamics within the leader streamer zone being quite complex. It is understood that plasma formations, known as

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space stems, detached from the main leader channel, play a key role in the negative leader's stepped propagation (Gallimberti et al., 2002; Gorin et al., 1976). In recent years, space stems have been observed in both natural and rocket-triggered lightning. They have luminosities comparable to the main leader channel, but appear detached from it, typically 1–8 m ahead of the leader tip. Additionally, space stems are typically between 1 and 10 m in length and sometimes occur in small groups ahead of the leader tip, generating between 1 and 3 luminous zones (Biagi et al., 2010, 2014; Gamerota et al., 2014; Hill et al., 2011; Jiang et al., 2017; Petersen & Beasley, 2013; Qi et al., 2016; Tran et al., 2014). The fact that space stems only appear in negative leader channels begs the question: *Are space stems the root cause of the polarity asymmetry between positive and negative leaders*, *or are they merely another symptom?* Other important symptoms of the polarity asymmetry include the large discrepancy in: leader speeds, very high frequency power emission, and channel branching (Mazur & Ruhnke, 2014; Williams, 2006). In this work we present streamer zone and space stem photographs with an unprecedented level of detail and image fidelity. In a particular example, it is possible to see the double-ended structure of a space stem with streamers emanating from both of its ends, creating an embryonic space leader (Montanya et al., 2015). This work is among the few observations of space stem occurrence in natural lightning available in the peer-reviewed literature (Hill et al., 2011; Petersen & Beasley, 2013; Qi et al., 2016).

2. Methodology

In order to observe lightning attachment to residential buildings, high-speed cameras were installed in São José dos Campos, Brazil. Several building tops were within the field of the view. The camera that captured the attachment process was a monochrome, 12-bit depth, 28-micron pixel size sensor Phantom v2012 camera using a Nikon 20 mm/F2.8D lens. This camera was set to operate at 40,000 frames per second with exposure times of 23.84 μs and time intervals of 25.0 μs. Image spatial resolution used for the flash herein described was 1,280 × 448 pixels. Each frame of the video was time stamped by means of a global positioning system antenna.

On 30 March 2021 a cloud-to-ground lightning flash containing five negative strokes made five different ground contacts. The negative leader of the second stroke started a different path to ground and connected to an UCL that was initiated on a chimney atop of a 27-story building, marked as building number **11** in Figure 1. The distance of the striking point to the camera was only 161 m and according to the lightning detection system, the peak return stroke current was −29.6 kA and occurred at 02:58:47.631051 UTC. Data from a 9-sensor lightning location system (LLS) were used to obtain the polarity, the time, and an estimate of the peak current of the return strokes observed. For the case analyzed in this work the location error of the LLS for the ground contact point of the flash observed was 188 m, which is considered very good. Further information about the LLS is provided by Morales et al. (2018).

Figure 2 shows some of the UULs initiated from buildings number **1**, **2**, **3**, **10**, **11**, **12**, and rods ***a*** and ***b*** in Figure 1. Remarkably this flash produced a staggering total of 31 upward leaders detected by our video cameras, only some of them appear in Figure 2 (images of other UULs are available in Supporting Information S1).

We manually analyzed 20 video frames preceding the lightning return stroke, spanning a 500 μs interval. In order to track leader characteristics as a function of time, each frame of the video was marked and each leader was labeled, as shown in Figure 2. We use a decimal notation (with a ".") to track branching in the negative leaders. Positive leaders do not require this effort as they do not branch. The attachment process happens when downward leader **15.5** connects to upward leader **6**.

In each camera frame, filters were applied, and data was collected concerning: leader tip position, streamer zone size/length, streamer zone morphology, and streamer count (details provided in Supporting Information S1). Length scales were converted from pixels to meters using the known story height in buildings **1** and **11**. All leaders on the left-hand side of Figure 2 were assumed to be at the distance of building **1**, which was 261 m. Similarly, all leaders on the right-hand side of the image, were assumed to be 161 m away, which is the distance to building **11**. Uncertainties were generated by accounting for the fact that the lightning flash may have occurred within 100 m of the actual striking location. The imagery suggests that all downward leaders hover over buildings **1** and **11.** The 100-m figure corresponds to the horizontal distance between the two buildings. The approach employed here generated upper bounds for the error in length estimates of roughly 19% and 31% for leaders on the left- and right-hand side of Figure 2, respectively. All reported distances and speeds given hereafter were measured in 2D and therefore are underestimated.

Figure 1. Buildings and structures observed by the camera installed in São José dos Campos, Brazil.

3. Results

Figure 3 shows the distance traveled by some of the leaders displayed in Figure 2. The slope in distance versus time gives the average leader speed within the video record. The UULs shown in Figure 3 have speeds of about 4×10^4 m/s, while the UCL is roughly 3 times faster, at 1.4×10^5 m/s. The UCL has a speed comparable to the average speed in the downward leaders, which is 1.2×10^5 m/s. The fastest downward leader is the downward connecting leader (downward connecting leader in Figure 3), which has a speed of 3.7×10^5 m/s. Statistical properties for the measured leader speeds are reported in Table 1. The values are comparable to what has been measured previously (Saba et al., 2017). The error in the determination of 2D distances was found to be within 20%–30%, and the coefficients of determination (R^2) of the linear fits used for speed calculation were higher than 0.96. The speed of negative leaders is tracked only for some dominant branches and from its root all the way down to its lowest point. For example, the position of leader **18.3.1.4** (on the left-hand side in Figure 2) is tracked all the way back to the top, when it emerges in the frame and is labeled as leader **18**.

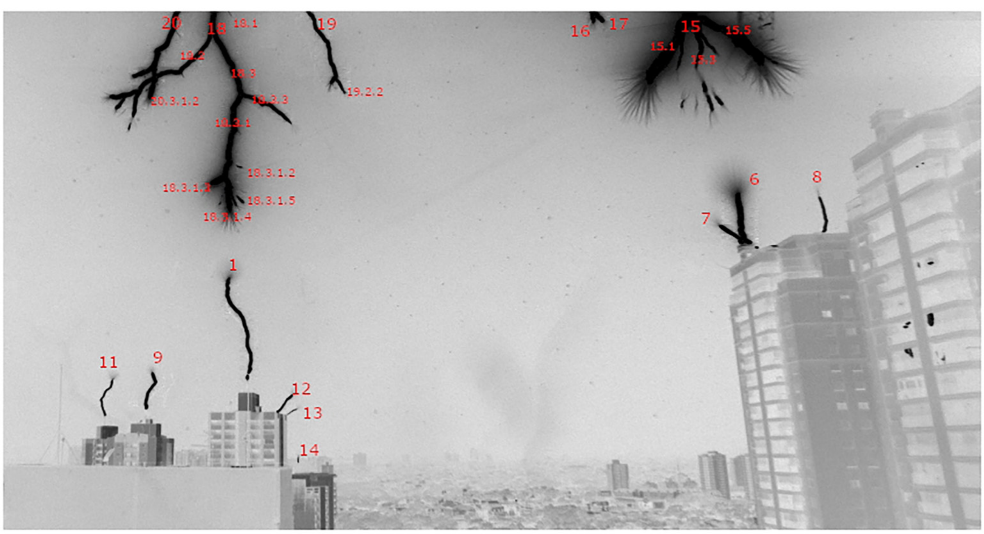

Figure 2. Lightning attachment to building **11**. This figure shows one frame before the occurrence of the return stroke.

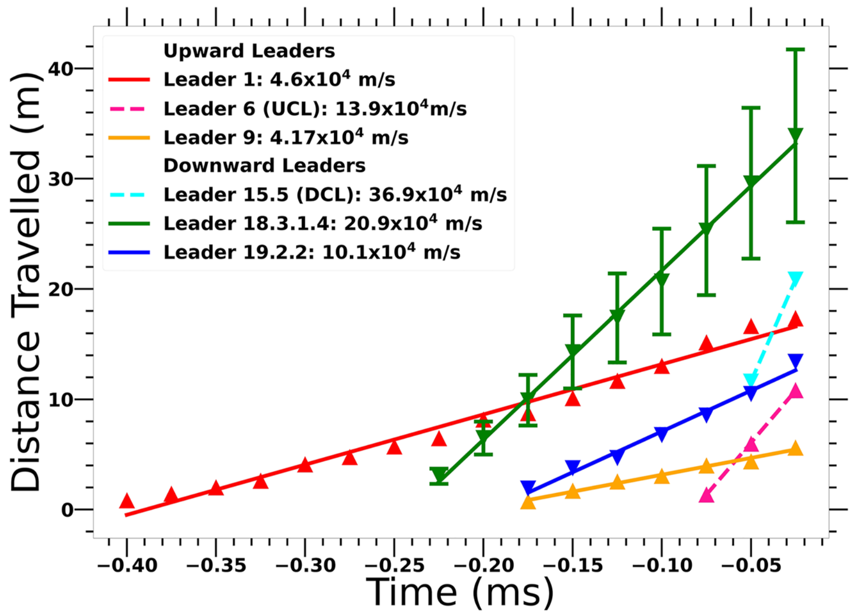

Figure 3. Distance traveled by some of the lightning leaders analyzed. The linear fit slope yields the leader average velocity, as listed in the figure legend. Upward and downward leaders are represented by upward- and downward-pointing triangles, respectively. Error bars are produced by propagating a ±50 m horizontal location uncertainty into vertical position uncertainties. Upward connecting leader and downward connecting leader stand for the upward and downward connecting leaders, respectively.

Upward leaders are seen to pulse a few times before setting their course. After ignition, upward leaders propagate continuously in the same general direction (seldomly straying abruptly from the same path), with its direction determined by the geometry of the downward leaders. For instance, UULs **12** and **13** travel toward downward leaders **15** and **16**. Upward leaders are not branched. Detailed analysis of the video frames indicates that leaders **6** and **7** most likely initiated in different locations in the building.

As the highly branched downward negative leader approaches the ground, it is possible to observe several streamers emerging from each leader branch tip. Figure 4a shows a zoom into leader **15** and its branches. Up to 14 easily distinguishable streamers are seen emanating from a single leader tip. Figure 4a shows two frames before the return stroke, while Figure 4b shows the subsequent one—the same one as shown in Figure 2. We can see that leaders **15.1** and **15.5** continue their propagation by emitting a fan of streamers from their tips. On the other hand, the dynamics for leader **15.3** is more complex. In the 25 μs time scale between the two frames, we see the emergence of space stems, highlighted in Figure 4c, and traced in magenta color in Figure 4d. These plasma formations appear in regions previously occupied by the leader streamer zone in the preceding frame, as it can

Table 1
Measured Properties for 20 Different Leaders (16 Upward and 4 Downward), 14 of Which Are Pictured in Figure 2

Feature	Sample size	Min	Max	Average	Average error
Upward leaders					
Size of corona brush (m)	10	0.7	3.0	1.2	±0.3
Speed (10^4 m/s)	9	3.2	13.9	6.3	±0.2
Downward leaders					
Number of streamers per leader tip	39	1	14	5	±1
Length of streamer zone (m)	39	1.1	5.5	2.5	±0.8
Space stem length (m)	4	1.5	2.4	1.9	±0.5
Distance between space stem and leader tip (m)	4	2.5	5.4	4.4	±3.4
Speed (10^4 m/s) (for dominant branches only)	4	10.1	36.9	12.1	±0.4

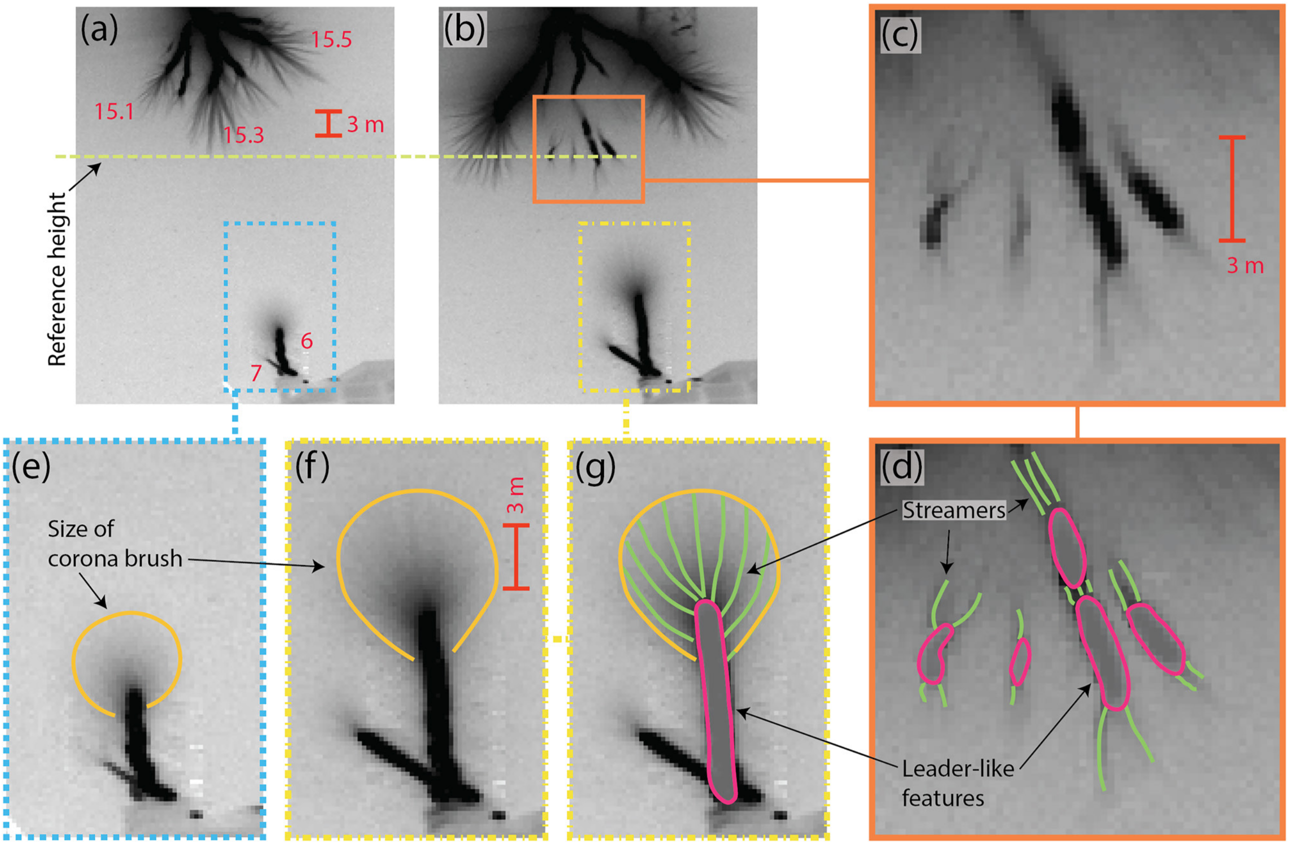

Figure 4. (a, b) Zoom into leader **15** for two consecutive video frames before attachment. (c, d) Further zoom into streamer zone and space stems of leader **15.3**. (e–g) Further zoom into upward connecting leader. Panels (d) through (g) show attempts to trace the leader- and streamer-like structures in magenta and green colors, respectively. Time between frames (a) and (b), and between (e) and (f) is 25 μs. A reference 3 m ruler is added to the three sets of panels for reference.

be seen by using the reference height line in Figures 4a and 4b. Additionally, the space stems have luminosities comparable to the main leader channel. Existing theoretical work suggests that the 25 μs time span between two frames is more than sufficient for heating of atmospheric air, which promotes streamer-to-leader transition (da Silva & Pasko, 2013; Malagón-Romero & Luque, 2019). In some cases, streamers can be seen emanating from the space stems, as traced in green in Figure 4d. Particularly, they appear to emit streamers from both ends, creating embryonic bidirectional space leaders (Figures 4c–4d). Space stems have lengths of about 2 m and appear 4 m away from the main leader tip. Other key properties of space stems are listed in Table 1. The numbers reported in Table 1 are comparable, but not identical to what has been previously found. For instance, Hill et al. (2011) found that space stems had longer lengths (of 4 m) but were located closer to the main leader tip (only 2 m away). But we note that Hill et al.'s observation was from a further distance away, of the order of 1 km (not precisely determined). Perhaps the observation geometry that is most similar to this work was attained by Qi et al. (2016). Based on observations from a distance of 350 m, these authors found that space stems have average lengths of 5 m and were located 4 m away from the leader tip.

In Figure 4, the upward leaders emerging from the building structure underneath are not branched, and each one of them presents a fan-shaped and uniformly luminous corona brush (traced in yellow in Figures 4e–4g). The length of the corona brush gets longer as the distance between the downward leader and the upward leader diminishes. The typical scale size for a corona brush is 1.2 m, as listed in Table 1. It is interesting to note that the UCL corona brush (Figure 4e) transitions into a more filamentary streamer zone just before connection (Figure 4f). The streamer-like structures are highlighted with green traces in Figure 4g.

Looking back into Figure 2, we can see that space stems appear in a number of other negative leaders, but (most importantly) not in all of them. For instance, we can see space stems in leaders **18.3.1.2** and **18.3.1.5**. This finding suggests that space stems are not a requirement for the negative leader propagation, but perhaps simply a

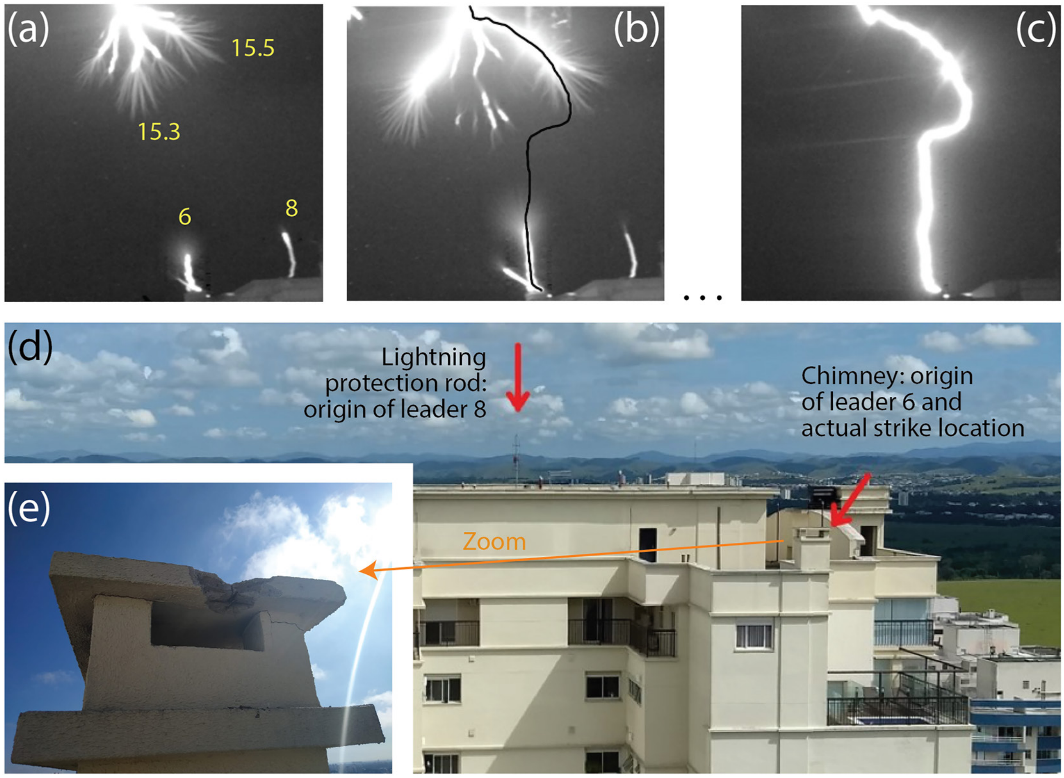

Figure 5. (a) Branched downward leader displaying multiple streamers. (b) Return stroke path traced over the frame (25 μs) just prior to the attachment. (c) Return stroke image 1 ms after attachment. (d) Lightning connected to chimney in the corner of the building despite the presence of a taller lightning protection rod at the top. (e) Destruction caused by the lightning strike.

byproduct of the intricate dynamics taking place in its streamer zone. Existing theoretical models of space stems hint on a possible physical mechanism that can explain their occurrence, but fail to explain why they only appear in negative streamer zones, and why they only appear in some cases. The most probable physical mechanism involves a plasma instability triggered by electron attachment to oxygen molecules in a decaying streamer channel (Malagón-Romero & Luque, 2019).

Figure 5 shows that, unexpectedly, it is leader **15.5** that connects to the longest upward leader (# **6**). Figure 5a indicates that the middle branch (**15.3**) may have been initially closer to the UCL, but the emergence of space stems seems to hamper its propagation (Figure 5b). As a consequence, the attachment process happens with both leaders intersecting at an angle of almost 90°. The upward leader that connected to the downward leader had its origin on the oven's chimney for the top-floor apartment (Figure 5d). Upward leader **8** had its origin on the single 3-m vertical rod of the building's LPS, but it failed to connect with any of the downward leaders. The unprotected chimney was severely damaged by the return stroke current and its fragments flew in all directions (Figure 5e).

In the discussion above, we suggested that the emergence of space stems hampered the leader propagation. Another interpretation could also be that space stems only appear in decaying leaders, right after they take their last step. Anyhow, we can say for certain that in most cases the descending leader does not follow the path in which a space stem is present. This happens to most, but not all cases. For instance, leaders 18.2 and 19.2 follow the space stem path (see videos in the data repository).

4. Summary and Conclusions

In this study, a very close high-speed video observation of lightning attachment to an apartment building revealed novel details regarding: leader propagation, the morphology of streamer zones in positive and negative leaders, and the appearance of space stems in negative leaders. A staggering total of 31 upward leaders were seen to originate from several buildings near the striking location. Upward leaders propagate in a steady and unbranched manner, with speeds of the order of 10^4 m/s. The UCL was the fastest of all upward leaders (3 times faster). Upward positive leaders have a "streamer zone" which does not seem to have any streamers at all. It resembles a uniformly luminous corona brush. The exception being the UCL just before connection, when its streamer zone transitions into a more filamentary pattern. The length of the corona brush gets longer as the distance between the downward and upward leaders is reduced. Downward negative leaders are heavily branched, and up to one order of magnitude faster than positive ones. We can distinguish multiple streamers emanating from each negative leader tip, with lengths of the order of 3 m. In some occasions, plasma formations known as space stems are seem to form in the location previously occupied by negative streamers. Space stems have luminosities comparable to the main leader channel, but are detached from it by 4 m. Some space stems display streamers of their own emanating from both ends, forming an embryonic bidirectional space leader. The space stem formation hampered the propagation of the negative leader that was (apparently) closest to the UCL, as a result the attachment process happened with a different downward leader branch, resulting in a connection at an angle of almost 90°.

Data Availability Statement

The high-speed videos and data analyzed in this work are available at: https://doi.org/10.5281/zenodo.7261368.

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