Polarity symmetry of leaders in moist air

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Abstract

The most important physics underlying lightning is the leader discharge. The presence or absence of space stems/leaders in leader steps is the key to the polarity asymmetry of leaders, which describes the difference in macroscopic behavior between positive and negative leaders and is a long-term consensus among lightning physicists. It is generally believed that negative leader steps are led by space stem, and there is no space stem/leader in positive leader discharges. Here we report the emergence of the space stem and the bidirectional development of the space leader in positive leader steps in moist air, using a high-speed camera with unprecedented spatial-temporal resolution. The lifetime of space stem/leader in positive leader steps is shorter than that in negative leader steps, causing the uncover of space stem/leader in previous studies. The bidirectional development of space leaders in positive leader steps may be an important source for VHF radiations, illuminating insight into the outstanding problem that how positive lightning leaders produce VHF radiation.

Introduction

Lightning is a commonly-experienced yet still mysterious natural phenomenon. The lightning's physical nature is that the thermally-ionized plasma channels, termed positive and negative leaders, extend in virgin air¹. The polarity asymmetry of positive and negative leaders, which describes the difference in macroscopic behavior between positive and negative leaders, is a consensus broadly accepted by lightning physicists². Negative leaders propagate by way of a stepping process led by space stems/leaders, with rapid elongations and sharp channel illuminations³⁻⁷. Positive leaders usually propagate continuously but also exhibit steps under particular conditions⁸⁻¹⁴. Space stems/leaders had never discovered in positive leader steps. It is generally believed that the stepping mechanism of positive leaders is different from that of negative leaders². The emergence or absence of space stems/leaders is the key to the polarity asymmetry of leaders. Copious radio electromagnetic pulses in the 30-300-megahertz frequency band are emitted during the negative leader steps^{4,9,15}, attributed to the space leader's bidirectional development^{16,17}. There are varying reports regarding VHF emissions strength from positive leaders. In some literature, positive leaders are quiet at VHF/UHF¹⁸, while some reports indicate that positive leaders radiate VHF rather more strongly than negative stepped leaders¹⁹⁻²³. It is puzzling that how positive leaders produce VHF radiation with the absence of space leaders²⁴. Here we report the emergence of space stems and the bi-directional development of space leaders in positive leader steps, discovered at the unprecedented spatial -temporal resolution. Our results suggest that high humidity during summer thunderstorms will break the polarity asymmetry of lightning leaders and illuminates insight into how positive lightning leaders produce VHF radiation.

Results

Bi-directional development of the Space leader in positive leader steps

Figure 1 shows the emergence of the space stem and bidirectional development of the space leader in a positive leader step. Frames #1 to #9 records the continuous development of the positive leader. A floating luminous formation was imaged by frame #7. The floating luminous formation emerged in the leader corona zone and at about 0.43 m from the descending positive leader tip. The brightness of the floating luminous formation is close to that of the primary leader channel, indicating that the temperature inner the floating luminous formation may also be close to the leader core's temperature. According to these features, the floating luminous formation can be identified as a space stem or a space leader. Comparison of frame #7 and frame #8 shows the bi-directional development of the space leader converted from the space stem. The upper end of the space leader propagated backward (toward the descending leader tip), and the lower end of the space leader developed forward. The estimated backward velocity of the space leader is larger than 1.58×10^5 m/s. The estimated forward velocity of the space leader is about 3 times the value, significantly larger than the velocity of continuously developing positive leaders. During the exposure duration of frame #8, the upper end of the space leader almost touched the descending leader tip, and the leader corona streamers emerged from the lower end of the space leader almost touched the ground. Thus, we infer that the space stem/leader lifetime (defined as the time from the emergence of the space stem to the full integration of the space leader into the primary leader channel in this letter) is less than $2.22 \mu\text{s}$ in the event.

Comparison of leader steps of different polarities led by space stems/leaders

Figure 2 shows the current pulse of a positive leader step led by a space stem and 3 consecutive frames recording the step. The space stem emerged at 0.13 m from the descending leader channel tip. We did not capture the bi-directional development of the space leader. That may be because the space stem/leader lifetime is short (less than $2.22 \mu\text{s}$). Thus, the process was masked by the subsequent process of strong luminescence within the same exposure duration. The current pulse exhibits different features in 3 stages. The first stage is referred to as the collision stage in this letter, characterized by the slow rise of current. The current features in this stage like those of the breakthrough phase reported by previous literature. We infer that the current rise in this stage corresponds to the collision of opposite-polarity streamers emerging from the descending leader channel tip and the space stem, respectively. The second stage is referred to as the burst stage here. When the space leader merges with the primary positive leader, the primary positive leader tip's high potential is transferred to the lower end of the space leader, followed by an intense positive leader corona streamers burst reported by previous literature. We infer that this stage's current rise corresponds to the burst of leader corona streamers, exhibiting a similarly sharp rise to streamer current pulses. The third stage is referred to as the decay stage here, lasting several microseconds.

Figure 3 shows the current pulse of a negative leader step led by a space stem and 6 consecutive frames recording the step. The space stem emerged at 0.4 m from the descending leader channel tip. The space stem/lifetime is longer than $4.44 \mu\text{s}$. The space leader's estimated backward velocity is larger than 6.7×10^5 m/s, which is close to the estimated forward velocity of the space leader shown in Fig. 1. According to different features, the negative leader step could also be divided into 3 stages, similar to the

positive leader steps led by the space stem. The difference is that the collision stage duration of the negative leader step (lasting about $3.5 \mu\text{s}$) is obviously longer than that of the positive leader step led by the space stem. The longer collision stage duration of the negative leader step may be associated with the longer space stem/leader lifetime in the negative leader steps.

In research, we often captured the space stem or space leader in positive leader steps, but the space leader's bi-directional development was observed only in only one step. However, the bi-directional development of the space leader in negative leader steps was frequently recorded in negative leader steps. That may indicate that the space stem/leader lifetime in positive leader steps tends to be shorter than in negative leader steps.

Discussion And Conclusions

The space stem/leader described above seems not the luminous crown residual²⁵, but there may be some relations with the space-leader-like segment reported by previous literature²⁶. The results reported here powerfully proves the existence of space stem/leader in positive leader steps, ending a long-standing argument²⁷. The intense leader corona streamers burst occurring after the space leader merges with the primary positive leader injects a strong current pulse into the leader channel. Current and luminosity waves then travel backward the leader channel, plausible with the lightning observations that the luminosity surge propagates back through the leader channel after a step^{10,28}, which is difficult to understand in the past. The current pulse of positive leader steps led by the space stems/leaders exhibits a sharp front. Current pulses of upward positive leader steps with the same feature were also registered in triggered-lightning observations²³. These facts indicate that the space stem/leader reported here may also exist in positive lightning leader steps. Due to the short lifetime of space stems/leaders in positive lightning leader steps, it was ignored by the previous photography systems.

VHF radiation from the positive lightning leaders is still not well understood. The needle-like discharge that may occur after positive leader development pausing is identified as a critical source. It is rational to infer that the collision of streamers with opposite polarity in the positive lightning leader steps led by space stems/leaders may be another important source.

The ambient absolute humidity during our experiments varied from 18 g/m^3 to 22 g/m^3 , closing to or less than the absolute humidity during the summer thunderstorms. In the hundreds of positive lightning-like discharges produced in a dry environment of which the absolute humidity is less than 7 g/m^3 , the step current pulse with a sharp front was not registered. That indicates the absolute humidity may play an important role in the emergence of the space stem/leader in positive leader steps. The emergence of space stems is favored in the streamers launched from the primary leader tip with the strong internal electric field²⁹. The internal electric field in negative streamers is more powerful than that in positive streamers under dry conditions³⁰. Therefore, it is not easy for space stems to emerge ahead of the propagating positive leader tips. However, water vapor molecules in the air have strong electronegativity, which can accelerate the electron attachment process in positive streamer channels. As the humidity

increases, the internal electric field in a positive streamer channel is enhanced. That may create a condition necessary for the emergence of space stems. On the other hand, the temperature is critical to the transition from the stem to the leader^{31–33}. When electrons flow along the stem, only a fraction of collisional energy loss is immediately transferred to the thermal energy of the gas molecules and contributes to the temperature increase. A larger fraction goes into the vibrational excitation of molecules. The vibrational energy relaxes into the thermal energy with a relaxation time constant, causing a delayed increase in temperature. The relaxation time is depended on the air humidity. As the humidity increases, the time constant decreases, and the space stem develops more easily into the space leader⁸. These two facts may explain why space leaders could emerge ahead of propagating positive leaders at a certain humidity.

Method

A rod-plane gap with meter scale was applied to standard switching impulse voltage to produce lightning-like leader discharges. The discharge current and applied voltage are measured simultaneously. A high-speed camera was used to record the dynamic processes of lightning-like leader discharges.

Due to the unpredictability of lightning, many critical insights about lightning have come from the laboratory lightning-like discharges^{2,34}. The space stem/leader leading to negative leader steps was first discovered in the laboratory^{35–37} and later confirmed through natural lightning observations³⁸. Supposing space stems/leaders also exist in positive leader steps, the reason that they had never been discovered even in laboratory lightning-like discharges may be that the lifetime of space stems/leaders in positive leader steps is short, and the spatial-temporal resolution of previous photography systems is insufficient to distinguish them. In our research, a super lens, whose aperture value (1:0.78) is little smaller than the aperture value (1:0.7, the largest in history) of the lens used to photograph the lunar in the Apollo Project, was applied. As a result, the framerate of the high-speed camera was upgraded to 900 000 FPS while ensuring satisfactory spatial resolution. In addition, thousands of laboratory-scale lightning-like discharges were produced in our research. Massive amounts of data create luck.

Declarations

Contributions

Shengxin Huang drafted the manuscript. Weijiang Chen supervised the research and revised the manuscript. Shengxin Huang, Yufei Fu and Zhiyuan Zhang conducted the experiments and processed the data. Zhong Fu, Weidong Shi, Nianwen Xiang and Dengfeng Cheng contributed to the data analysis.

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Figures

Figure 1

Space stem/leader emerged in positive leader tip's vicinity. The above panel is the enhanced processed high-speed video frames recording the discharge before and after the space stem. The middle panel shows the exposure duration of each frame. The bottom panel shows the heatmap of the grayscale value

of pixels in unprocessed (origin) frames #6 to #8. These origin frames are 16 bit in depth. The deepest red is corresponding to the maximum grayscale value of 682. The lightning-like discharge is produced by applying the standard positive switching impulse (SI) to a 4 m point-to-plane gap in the summer of 2020. The absolute humidity is about 20 g/m³, the air pressure is 1 atm.

Figure 2

Positive leader step current pulse and frames recording the step. The above panel shows the step current pulse of a positive leader led by a space stem. The bottom panel shows the heatmap of the grayscale value of pixels in unprocessed (origin) consecutive frames recording the step. These origin frames are 16 bit in depth. The deepest red is corresponding to the maximum grayscale value of 682. The lightning-like discharge is produced by applying the standard positive switching impulse (SI) to a 4 m point-to-plane gap in the summer of 2020. The absolute humidity is about 22 g/m³; the air pressure is 1 atm.

Figure 3

Negative leader step current pulse and frames recording the steps. The above panel shows the step current pulse of a negative leader led by a space stem. The bottom panel shows the heatmap of the grayscale value of pixels in unprocessed (origin) consecutive frames recording the step. These origin frames are 16 bit in depth. The deepest red is corresponding to the maximum grayscale value of 682. The lightning-like discharge is produced by applying the standard negative switching impulse (SI) to a 2 m

point-to-plane gap in the summer of 2020. The absolute humidity is about 22 g/m³; the air pressure is 1 atm.