Propagating features of upward positive leaders in the initial stage of rocket-triggered lightning

Rubin Jianga,b, Xiushu Qiea,⁎, Caixia Wanga,b, Jing Yanga

a Key Laboratory of Middle Atmosphere and Global Environment Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
b Graduate University of Chinese Academy of Sciences, Beijing, China

ABSTRACT

The propagation characteristics of upward positive leaders in the initial stage of rocket-triggered lightning flashes have been analyzed using high-speed video images, channel base currents, and electric field changes. The luminous intensity at the tip of leader steps was stronger than that in the channel behind it. The average 2-D speed of the leader was $1.0 \times 10^5$ m/s with partial speeds ranging from $2.0 \times 10^4$ m/s to $1.8 \times 10^5$ m/s between 130 m and 730 m above ground. The leader speed showed an obvious irregularity and an accelerating tendency with height and time. Unipolar current pulses, with peak currents ranging from tens of amperes to about 150 A, were observed at the ground during the initial stage of leader development. The electric field change showed stepped waveforms at this stage and it was evident that the leader involved a stepwise propagating mode. For 34 current pulses occurring in the initial stage of the leader development, the geometric mean values of the peak current, rise time, half peak width, duration, charge transfer and pulse interval were 45.0 A, 0.49 μs, 0.99 μs, 3.2 μs, 4.8 μC and 19.9 μs, respectively. After the leaders extended to several hundred meters above ground, fluctuations were found to be superimposed on the continuous current and the associated electric field.

1. Introduction

Prior observations have confirmed that there are distinct differences between the leaders of different polarities. In contrast to negative leaders propagating in virgin air, which always propagate optically stepped, positive leaders in virgin air can develop continuously or step-wise (Berger and Vogelsanger, 1966; Rakov and Uman, 2003; Kong et al., 2008). The VHF radiation produced by positive leaders is much weaker than negative leaders (Mazur and Ruhnke, 1993; Shao et al., 1999; Thomas et al., 2001; Mazur, 2002). The electric field waveforms radiated by positive leaders are likely to exhibit less stepping as they approach the ground than the leaders in negative lightning (Rakov and Uman, 2003).

Due to the relatively rare occurrence of positive lightning and the weakness of the VHF radiation from positive break down processes compared to the negative on, it is more difficult to conduct experiments on positive leaders than on negative leaders in natural lightning. Classical triggered lightning starts with the initiation and then the sustained propagation of an upward positive leader (Wang et al., 1999; Willett et al., 1999; Rakov et al., 2003, 2005; Yang et al., 2009), providing a good opportunity of studying the luminous evolution of this kind of leader, together with simultaneous measurements of the current and the associated electromagnetic radiation. The speeds of the extending upward positive leaders in triggered lightning were observed to range from $-10^4$ m/s in the very early stage when they begin at the wire tip (Fieux et al., 1978; Laroche et al., 1985; Biagi et al., 2009), to $-10^6$ m/s when they reach an altitude of 1–3 km above the ground (Yoshida et al., 2010), which indicates an acceleration of

⁎ Corresponding author at: Key Laboratory of Middle Atmosphere and Global Environment Observation (LAGEO), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China. Tel.: +86 010 82995091; fax: +86 010 82995073.
E-mail address: qieox@mail.iap.ac.cn (X. Qie).

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upward positive leader (Yukio et al., 1985; Yoshida et al., 2010). Both the continuous and the stepped modes of propagating have been observed during their development. Willett et al. (1999) and Lalande et al. (1998, 2002) found that during the early stages of the positive leader development in triggered lightning, the channel base current exhibited oscillating impulsive current waveforms, which indicated step-wise development of the leader (during the corresponding stage). Rakov et al. (2003) studied the initial stages of rocket triggered lightning and found current variations during the initial continuous current and fluctuations on the E-field ramp, also suggesting step formation processes of the upward positive leader. Yoshida et al. (2010) found that the high speed video images (with the time resolution of 3.3 μs) of an upward positive leader showing 10 discrete steps in the first 11 m of development were correlated with impulsive current recordings.

In this paper, we will examine the characteristics of upward positive leaders that showed obvious step-like features during the initial stage of their development, based on high speed video that were correlated with the measurements of currents at the channel base, and electric fields measured at 60 m from the channel.

2. Experiment and data description

The flashes analyzed in this study were recorded during the SHandong Artificial Triggering Lightning Experiment (SHATE) in 2010. The SHATE experiment, which was designed to explore the close electromagnetic environment of lightning channel and its relationship to the discharge current, and to study the effects of lightning on ground objects, has been operated continuously since the summer of 2005 (e.g., Qie et al., 2007, 2009; Yang et al., 2010). A kind of newly-designed rocket, made of composite material and assembled with parachute (Qie et al., 2010), has been used since 2009. The surface electric field is referred to launch rocket for triggering lightning, although the hard measured electric field aloft is more indicative (Qie et al., 1994).

Four negative lightning flashes, named 201001, 201002, 201004 and 201005 that were triggered in the summer of 2010, have been used to study the propagation characteristics of positive leaders. The optical evolution of the discharge channel and current at the channel base were measured simultaneously for flash 201001, and the currents and electric fields were obtained for flashes 201002, 201004 and 201005. The high-speed optical imaging was obtained using a Photron FASTCAM SA1 camera, which was located 670 m away from the rocket launcher. The camera was operated with a time-resolution of 100 μs (10,000 fps) and a spatial resolution of 576 × 832 pixels, and the lens focal length was 16 mm. Calibration shows that a unit pixel stands for an area of 1.0 m² over the rocket launcher. The channel base current was measured using a 0.5 mf1-shunt with a bandwidth of 0–3.2 MHz and a Pearson coil with a bandwidth of 0.9 Hz–1.5 MHz. The signals were transmitted via an optical fiber system (ISOBES5600, bandwidth: 0–20 MHz) to a DL750 oscilloscope and were digitized at a 0.1-μs sampling interval. The total recording length was 1.0 s. The electric fields were measured using both slow and fast antennas with time constants of 3 s and 1 ms and bandwidths of 2 MHz and 5 MHz, respectively (Qie et al., 2011).

3. Analysis and results

3.1. The speed in the initial several-hundred-meters and the associated intermittent nature of upward positive leader

Fig. 1 shows the images of initial propagation of an upward positive leader in triggered lightning 201001, corresponding to a height range from 130 m to 730 m above the ground. The time interval between each image in Fig. 1a is 100 μs. A unit square (a single pixel) in Fig. 1b and c stands for an area of 1.0 m². The leader emerged from the wire tip at an altitude of 130 m and exhibited an erratic direction during its ascent. The images clearly show that the luminosity was enhanced at the leader tip, especially in the initial stage when the entire channel was rather faint.

Fig. 2 shows the 2-D partial speed of the extending positive leader that was retrieved frame by frame using the images shown in Fig. 1a. Fig. 2 clearly shows that the leader speed is irregular, which suggests that the extending process was intermittent. The average 2-D upward speed of the propagation is estimated to be 1.0 × 10⁵ m/s with partial speeds ranging from 2.0 × 10⁴ m/s to 1.8 × 10⁵ m/s. Even though the variation of speeds was significant, there clearly was an acceleration during the upward extending process. Yukio et al. (1985) once found a similar acceleration in the upward-going positive leaders in winter thunderstorm triggered lightning with a final speed that was 5 to 10 times greater than the initial speed. Laroche et al. (1985) reported a speed of about 10⁴ m/s for initial, upward-going positive leaders in rocket-triggered lightning. Biagi et al. (2009) showed a sustained upward positive stepped leader that developed at a constant speed of 5.6 × 10⁴ m/s over its initial 100 m in an altitude triggered lightning flash. Our results are consistent with previous observations. Although Biagi et al. (2009) showed no obvious variation in speed, it is not the opposite of the acceleration tendency, for their results were only related to the initial 100 m of the leader development. Kong et al. (2008) reported a natural downward-propagating positive leader that exhibited stepped-like characteristics and the 2-D propagation speed ranging from 0.1 × 10⁴ m/s to 3.8 × 10⁵ m/s. Saba et al. (2008) reported 39 partial speeds for 9 positive leaders, that oscillated between 0.23 × 10⁵ m/s and 13.0 × 10⁵ m/s with a geometric mean (GM) value of 1.8 × 10⁵ m/s. The speeds studied here for upward positive leader are generally consistent with those for the natural downward positive leaders presented by Kong et al. (2008) and Saba et al. (2008), but they are lower than those obtained recently by Wang and Takagi (2011), which were about 10⁶ m/s at the beginning (272 m to 93 m above ground) and then accelerated to 2.5 × 10⁶ m/s when getting near to the ground (about 45 m above ground). It is necessary to note that all the speeds mentioned above were obtained in the 2-dimensional observational plane of the leaders, which will of course lead to a lower estimate of the real propagation speed. Yoshida et al. (2010) acquired the VHF sources for two upward positive leaders which were sufficient to measure
speeds from 1.1 km to 2.4 km and 1.5 km to 3.7 km, and they obtained average 3-D speeds of $2.2 \times 10^6$ m/s and $3.3 \times 10^6$ m/s, respectively. These results are reasonably larger than the values in this paper. Because they were for 3-D, and the correlated altitudes were much higher than that showed in Fig. 1.

### 3.2. Step-like features during the initial stage of positive leader

Fig. 3 shows the current measured at the channel base (also the wire base), coordinated with high speed video frames (in the very initial stage) on expanded dimension, for the triggered lightning flash named 201001. As in Fig. 3b, eleven current pulses are definitely recognized during the very initial stage of the upward positive leader, with the peak currents ranging from tens of amperes (A) to about 150 A. These current pulses are unipolar and show sharp waveforms, the rise time is about 1 μs or less. The intervals between two adjacent pulses range from 20 to 40 μs (most approximately 30 μs). These current pulses, gradually weakened in intensity and increased in duration, disappeared till the initial continuous current was detectable. Willett et al. (1999) and Lalande et al. (1998, 2002) reported similar current pulses associated with the inception of upward positive leaders in classical triggered lightning, of course, their records exhibited damped oscillating waveforms, while the currents here are unipolar pulses. As stated in their papers, the oscillating current pulses had similar waveforms to the so-called precursors, which were resulted from the aborted leader attempt processes, and had pulse-intervals up to the order of milliseconds (or longer). For the current pulses shown in Fig. 3b, the corresponding video images clearly demonstrate the emergency and the following up-going of the leader from the wire tip, indicating that these current pulses were correlated with (or produced by) the leader development. Based on the above, we can confirm that the propagating mode of the upward positive leader is stepped during its very initial stage. Considering that the time interval between two adjacent current pulses is about 30 μs, it is estimated that 3–4 steps may occur during an interval of 100 μs, and the adjacent images in Fig. 3b show that the leader extended 5–10 m during each 100 μs at the beginning of its upward development, so we can infer that

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**Fig. 1.** Images of upward positive leader captured by a high-speed video camera operated at 10,000 fps in a triggered negative lightning flash 201001. (a) For the first 80 images of the extending leader, (b) for one image of the lightning channel after the wire evaporation, (c) for 4 expanded images revealing the leader emergence from the wire tip, (d) for 3 expanded images of the leader ascending process.

**Fig. 2.** Evolution of 2-D speed of the ascending positive leader based on the adjacent images in Fig. 1. There are a few missing values in the figure because the luminosity of some images is too weak to reveal the related speed.
the length of the individual step is in the range of 1–4 m. Biagi et al. (2011) once directly checked the images (by high speed camera operated at 300 kfps) of an upward positive leader, and distinguished 10 discrete steps during the initial 11 m development of the leader. The step-lengths were found to range from 0.4 to 2.2 m, being a little bit shorter than the estimated length here.

When discussing the current waveforms and their associated characteristics, an important fact is that the current sensors were installed at the wire base (which was also the channel base after the wire destruction). Hence, although sharp current pulses were correlated with the extending of the upward leader, these measured current waveforms may be actually not a real representation of the discharge process (or the charge deposited to a new extended section) of the leader, because there was a transmission process of the current signals through the triggering wire. The oscillating behaviors of the current pulses (Willett et al., 1999; Lalande et al., 1998, 2002) may be caused by the current reflections that occurred both in the wire tip and the ground (Biagi et al., 2011), and the incident current impulse due to a single leader step injecting charge to the leader and wire should physically be unipolar. It seems that the disappearance of the oscillation in the current pulses obtained here may be due to the larger resistance (compared with the other artificially triggering lightning experiment such as ICLRT) of the triggering

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**Fig. 3.** Current measured at the channel base for the upward positive leader of lightning 200101: (a) the whole waveform on timescale of 10 ms, (b) the current pulses in the very initial stage of the leader development, coordinated with the high speed video images, (c) the current waveform on expanded timescale from 5 to 5.5 ms.
wire [private communication with V. A. Rakov, in the forum of APL 2011]. Nevertheless, there could be no doubt that the current pulses are indicative of abrupt discharge processes associated with a step-wise development of the leader. Recently, by analyzing the observation data of optics, current and electric field, Biagi et al. (2012) studied in detail the characteristics of precursors which have similar current waveforms to the pulses at the initial stage of the UPL, and they confirmed that the precursors were due to electrical breakdown at the tip of the extending wire.

Unfortunately the electric fields during flash 201001 were not well recorded. In order to show additional properties of upward positive leaders, Fig. 4 shows the simultaneously measured channel base current and electric field changes for the triggered lightning 201005. In Fig. 4a, the waveform of electric field change in the very initial stage of the leader development is significantly stepped. The E-field steps and the current pulses are definitely matched to each other. Such stepping in the electric field is indicative of a transient injection of positive charge into the new channel section associated with a single step of the leader. In order to investigate a possible relationship between the E-field steps and the current peaks or the associated charge transfers, Table 1 shows in detail the corresponding values of the first ten pulses in Fig. 4a. Here, it should be noted that the magnitude of E-field steps is better correlated with the charge transfer than the pulse peak, although no quantitative fitting curves with significant correlativity can be conducted for both couples.

### 3.3. Characteristics of the current pulses at the beginning of the upward positive leaders

Table 2 shows the geometrical mean and ranges of parameters for the current pulses during the initial stage of 4 upward positive leaders, corresponding to the triggered lightning 201001, 201002, 201004 and 201005. The GM values of the peak current, rise time, half peak width, duration, charge transfer and pulse interval for 34 leader pulses were 45.0 A, 0.49 μs, 0.99 μs, 3.2 μs, 4.8 μC and 19.9 μs, respectively. It was previously reported by Laroche et al. (1988) and Lalande et al. (1998) that the current pulses associated with the stepwise developments of the upward positive leaders involved mean intervals of 20 μs or so. Biagi et al. (2011) analyzed ten similar current pulses and got an arithmetic mean of 21.2 μs for the same parameter, which ranged from 16.6 to 30.4 μs; the mean measured peak current of the pulses was found to be 59 A (based on the data showed in their paper, the geometric mean value is 43 A). All these results are in good agreement with results presented in this paper.

As shown in Table 2, the GM peak current for the leader-related pulses in flash 201001 was 76.7 A and the corresponding values for flash 201004 was 23.2 A, and meanwhile, the charge transfer during a single pulse in flash 201001 was larger than that of flash 201004. For the pulse interval of flash 201005, the GM value was 15.6 μs with a minimum of 12.5 μs, smaller than other three flashes. The waveform parameters of current pulses for different flashes exhibit some differences. This may be due to the different ambient fields at the triggering moment, which may influence the feature of the inception pulses, especially their intensity.

### 3.4. Fluctuations of current and electric field when the leaders extend to several hundred meters above ground

At about 4.5 ms after the leader emergence of lightning flash 201001, the leader tip reached an altitude of about 400 m. Fig. 3c shows the corresponding current record on expanded timescale. There were obvious fluctuations, with amplitude of approximately 20–30 A, superimposed on a slowly varying continuous current of about 50 A. Similar fluctuations can be

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**Table 1**

<table>
<thead>
<tr>
<th>No. of the pulse</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak current (A)</td>
<td>44</td>
<td>37</td>
<td>24</td>
<td>61</td>
<td>31</td>
<td>27</td>
<td>53</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Charge transfer (μC)</td>
<td>32</td>
<td>33</td>
<td>49</td>
<td>39</td>
<td>55</td>
<td>39</td>
<td>32</td>
<td>58</td>
<td>39</td>
<td>56</td>
</tr>
<tr>
<td>E-field change (V/m)</td>
<td>15</td>
<td>18</td>
<td>23</td>
<td>17</td>
<td>24</td>
<td>17</td>
<td>24</td>
<td>17</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>
also found in Fig. 4b (for the leader of lightning flash 201005), with the background continuous current enhancing gently. As simultaneously shown in Fig. 4b, the associated electric field change at 60 m had fluctuations superimposed on the ramp, with time interval of about 10–15 μs. Such fluctuation of current and electric field change indicate a discontinuous nature (but not distinct stepped nature) of the ascending positive leaders when they reach an altitude of several hundred meters above ground. It is necessary to note that the electric field showed well stepped waveforms in the very initial stage (as in Fig. 4a) while imperfectly stepped waveforms in the ascending process (as in Fig. 4b). The sharp current pulses which definitely correspond to stepwise propagating mode of the leader can only be found during the very initial stage of the leader development. Rakov and Uman (2003) once studied the electric field of the classical triggered lightning, and found that small variations which were probably associated with upward-positive-leader steps, occurred both before and after a so-called V-shaped electric field change (see their Figs. 1, 4 and 7). They considered the term “stepping” to be an impulsive process that periodically illuminates the extending leader channel. Wang and Takagi (2012) analyzed the optical data of the upward positive leaders that initiated from a windmill, and recognized several optical pulses during the initial stage of the leader. Since the observed optical pulses have longer rise time than negative leader steps, they termed this phenomenon as luminous-variation-events (LVEs).

Table 2
Geometrical means and ranges of parameters for the current pulses in the very initial stage of the leader development.

<table>
<thead>
<tr>
<th>Flash</th>
<th>Sample</th>
<th>( I_0 ) (A)</th>
<th>( \tau_{0-\text{rise}} ) (μs)</th>
<th>( \tau_{\text{HPW}} ) (μs)</th>
<th>( \tau_{\text{FW}} ) (μs)</th>
<th>( Q ) (μC)</th>
<th>( \tau_{\text{int}} ) (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>201001</td>
<td>11/9*</td>
<td>GM 76.7 0.54</td>
<td>1.08 3.3</td>
<td>99 25.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min 32 0.3</td>
<td>0.6 1.2</td>
<td>72 20.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max 163 0.9</td>
<td>1.8 7.1</td>
<td>174 33.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>201002</td>
<td>8/5*</td>
<td>GM 42.9 0.48</td>
<td>0.96 4.0</td>
<td>54.3 19.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min 19 0.2</td>
<td>0.5 1.4</td>
<td>36 16.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max 76.8 1.2</td>
<td>1.9 8.9</td>
<td>78 22</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>201004</td>
<td>5/2*</td>
<td>GM 23.2 0.38</td>
<td>0.90 2.5</td>
<td>25.6 19.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min 15 0.2</td>
<td>0.6 2.3</td>
<td>20 16.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max 39 1.1</td>
<td>1.7 2.8</td>
<td>37 23.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>201005</td>
<td>10/8*</td>
<td>GM 35.4 0.50</td>
<td>0.96 2.9</td>
<td>42.1 15.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min 24 0.2</td>
<td>0.6 1.7</td>
<td>32 12.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Max 71 1.3</td>
<td>1.5 6.3</td>
<td>58 18.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>total 34/24*</td>
<td>GM 45.0 0.49</td>
<td>0.99 3.2</td>
<td>54.8 19.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min 15 0.2</td>
<td>0.5 1.2</td>
<td>20 12.5</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Max 163 1.3</td>
<td>1.9 8.9</td>
<td>174 33.5</td>
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</table>

Note: *The sample number of the pulse interval (\( \tau_{\text{int}} \)).

4. Conclusion

Four ascending positive leaders in rocket-triggered lightning flashes have been analyzed. The evolution of the upward propagation speed show an obvious irregularity, but an accelerating tendency with height and time is also observed. The average 2-D speed of the leader was 1.0 × 10^3 m/s with partial speeds ranging from 2.0 × 10^3 m/s to 1.8 × 10^3 m/s. The luminous intensity at the leader tip was stronger than that at the channel behind it. Current pulses and stepped E-field waveforms during the very initial stage of the leader development were clearly recognized, indicating a stepwise propagation of the leader (during the corresponding stage). The 34 current pulses from 4 leaders showed the geometric mean peak current, rise time, half peak width, duration, charge transfer and pulse interval of 45.0 A, 0.49 μs, 0.99 μs, 3.2 μs, 4.8 μC and 19.9 μs, respectively. When the leader extended to several hundred meters above ground, fluctuations were found to be superimposed on the continuous current and the associated E-field ramp, implying a discontinuous propagating of the leader.

To date, increasing observational facts have been obtained to reveal the complicated behaviors of the positive leader, and evidence of intermittent development of positive leaders has been acquired by different researchers. Besides upward positive leaders in triggered lightning (as analyzed in this paper), downward positive leaders in natural lightning and those positive leaders (or streamers) generated by long laboratory sparks (Domens et al., 1991; Gu et al., 2010) have also been found to propagate intermittently in some instance. Kong et al. (2008) found that a positive leader obviously developed a stepwise fashion as it descended toward ground. Wang and Takagi (2011) also reported a downward propagating positive leader that radiated optical pulses like a negative stepped leader.

Although much is known about positive leaders, the defined physical mechanism that leads to the propagation of positive leader is still not clear, especially the cause of the stepping behavior. When a negative leader breaks down virgin air, the step is considered to be produced by a connection of the secondary leader channel section (initiated by a space stem that develops bi-directionally) to the primary leader channel. Biagi et al. (2010) once observed distinct luminous segments ahead of the negative leader channel in triggered lightning, which confirmed the stepping mechanism of the negative leader. While for positive leader, it seems that similar connection process does not exist in the leader tip (Domens et al., 1991), and the steps were considered to be a result of the leader breaking and re-starting process (e.g., Domens et al., 1991; Rakov and Uman, 2003). Of course, what still remains confusing is that such breaking and re-starting of the leader could not interpret well the current pulses in the very initial stage of the upward leader development in triggered lightning, for those current pulses showed quite short rise time and duration, indicating an abrupt discharge process of the leader.

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