Journal of Atmospheric and Solar-Terrestrial Physics 173 (2018) 128–139

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The luminescence characteristics and propagation speed of lightning leaders

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ARTICLE INFO

Keywords:
Lightning
Leader
Light intensity
2-D propagation speed

ABSTRACT

The light intensity and 2-D propagation speed of the leader channel of natural lightning are obtained by analyzing the optical data captured by a high-speed camera. For the leader channels of cloud-to-ground (CG) lightning, attempted CG lightning and bidirectional leader lightning, the light intensities present a pulse at the positions where the tip of the leader arrived, and as the tip passed, the pulse disappear and the light intensities of the channel remain stable. As the stepped leaders approach the ground, the tip luminous intensities and two-dimension (2-D) propagation speed of the channels as a whole shown the tendencies of "increased", "decreased" and "irregular" with time. Moreover, the luminous intensities of the tip or total channel increase when the branch occurred, while the propagation speed of stepped leader decreases in most cases.

1. Introduction

The propagation characteristics of stepped leaders are important to the research on the physical mechanisms of lightning initiation. High-speed camera is used to study propagation features of lightning leader because it can provide the light intensity and geometric characteristic with high time-space resolution. Zhang et al. (2009) reported the average speeds of the downward negative stepped leaders for channels with multi-branch and no branch based on four natural negative cloud-to-ground (CG) lightning flashes captured by high-speed camera. Stolzenburg et al. (2013) estimated 2-D speeds for visible initial leader or streamer. Campos et al. (2014a) calculated the 2-D speeds of leaders and obtained their statistical properties. Kong et al. (2015) gave the speed for downward positive leader of cloud-to-ground (CG) lightning. Meanwhile, more attention was given to the time evolution of the propagation speeds of negative leaders of cloud-to-ground lightning (e.g., Campos et al., 2014a; Lu et al., 2013; Lu et al., 2015). In addition, based on the Thunder and VHF lightning Locating System (TVLS), Qiu et al. (2015) investigated the influence of branching on the propagation speed when the negative cloud-to-ground lightning approaches ground.

The light intensity is closely related to discharge characteristics of lightning. The correlation between optical signals and the corresponding electric field change has been analyzed (e.g., Guo and Krider, 1982; Light et al., 2001; Jordan and Uman, 1983). According to optical images, a number of the studies have been reported on the propagation characteristics of lightning leader (e.g., Lu et al., 2008b; Zhang et al., 2009; Stolzenburg et al., 2013). However, studies based on digital image information are still lacking. Works on this respect will lay the foundation for the further quantitative study on the propagation characteristics of lightning leader. Based on digital image information, Jordan et al. (1997) reported that the light intensity for dart leader is more or less constant as the leader approaches the ground, Chen et al. (1999) investigated the light intensities of two downward stepped leaders recorded by a high-speed digital photodiode array photographic system. Using the data from Automatic Lightning Progressing Feature Observation System (ALPS), Wang and Takagi (2011) reported that the optical features of the positive downward stepped leader are quite similar to those of a downward negative stepped leader. The luminescence characteristics were also studied for branched lightning channels by high-speed digital optical system (Lu et al., 2008a; Wang et al., 2000).

In this paper, based on the optical data captured by high-speed camera, the time evolution of luminous intensity on different positions along channel for stepped and dart leaders are discussed, and the 2-D propagation speeds of stepped leaders are estimated. Meanwhile, the influences of the branches on the luminous intensities of main channel and 2-D propagation speed for stepped leader are explored.

2. Instruments and methods

In the summer of 2014, lightning field observation experiments were

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https://doi.org/10.1016/j.jastp.2018.03.006
Received 11 January 2017; Received in revised form 4 January 2018; Accepted 10 March 2018
Available online 30 April 2018
1364-6826/

Table 1
Parameters of the high-speed camera M310.

Maximum resolution @ Shooting rate	1280 × 800 @3260 fps
Maximum frame rate	650,000 fps
Pixel size	20 μm
Minimum exposure time	1 μs
Record time	1280 × 800@3260 fps:3G(0.64 s) 6 G (1.29 s) 12 G (2.57 s)

Table 2
Shooting parameters for images of the six flashes.

Name (Type)	Recording speeds(fps)	Pixel resolution
A(CG)	9663	960 × 384
B(CG)	9663	960 × 384
C(attempted CG)	9663	960 × 384
D(attempted CG)	13878	640 × 384
E(bidirectional leader lightning)	10288	896 × 384
F(bidirectional leader lightning)	9663	960 × 384

conducted in Qinghai Plateau of China. The altitude of the observation site is about 2500 m, where thunderstorms occur frequently. The weather temperature was about 20 °C. Lightning images were captured by a high-speed camera that was synchronized time-stamp with GPS. The high-speed camera was a M310 produced by American Phantom Company, and its parameters are listed in Table 1.

The light intensity of channel is obtained by integrating the gray value of pixels over the diameter of lightning channel. The tip luminous intensity of leader is the average gray value for many consecutive pixels on the leader head. The distance from the observation site to the discharge channel was estimated according to the difference of time of arrival between light and thunder. Due to the observation distance usually contain inaccuracy to some extent, the channel length and 2-D propagation speed of stepped leader was also estimated values.

3. Analysis and results

Six stepped leaders and two dart leaders from six natural lightning flashes are analyzed in this paper. The six lightning flashes are named flashes A, B, C, D, E and F. Flashes A and B are negative cloud-to-ground (CG) lightning. Flashes C and D are attempted CG lightning. Flashes E and F are bidirectional leader lightning. The recording speeds and pixel resolutions of the images for the six lightning flashes are listed in Table 2.

3.1. Light intensity of channel

3.1.1. Cloud-to-ground lightning

The images of main and entire channels created by downward stepped leaders of flash A are presented in Fig. 1(a) and (b), respectively. Some sample points along the channel, which are marked by arrows with numbers (in meters) in Fig. 1(c), are selected to investigate the light intensity of the channel. Meanwhile, Fig. 2(a) and (b) show the images of main and entire channels with inverted gray scale created by downward stepped leaders of flash B, and the selected sample points for investigations are marked in Fig. 2(c). The branches of the main channel are marked by the letter b with a subscript in the entire paper. The lengths of visible channels obtained by accumulating the pixel points along the curve channel are about 1560 m for flash A and 1370 m for flash B. Light intensities at sample points along the lightning channels as functions of time are presented in Fig. 3(a)-(c) for the stepped leaders of the flashes A and B, and the dart leaders preceding the second return-stroke (R_2) of the flash B, respectively. It is found from Fig. 3 that the light intensities of the channels for the stepped leaders A and B appear as pulses at the positions where the tips of the leaders arrived (simply “the first pulse” for short). The peak values corresponding to the first pulse are listed in Table 3.

As shown in Fig. 3(a), as well as Table 3, the peak values of light intensity at the sample points of 473 m, 414 m, 365 m, 266 m and 148 m are about two times greater than those at other positions. There are branches b_1 and b_2 at 473 m and 148 m (in Fig. 1(b)) of the channel, which may lead to the increase of light intensities around them, such as sample points of 473 m, 414 m, 365 m, 266 m and 148 m. When the tips of stepped leaders passed, the pulses of light intensities of channels disappear and the light intensities almost remain stable before the stepped leaders approach the ground. For instance, the light intensity is stable from about 2500 μs to 10000 μs at the sample point of 986 m of flash A (Fig. 3(a)). Additionally, Fig. 3(a) shows that the light intensities increase slightly when the stepped leaders of flash A get closer to the ground (as seen in Fig. 1(a)).

From Fig. 3(b), it is also found that when the tips of stepped leaders passed through the sample points along the channel, the pulses disappear and the light intensities remain stable for flash B. But the pulses of light intensities appear again on the positions from 1158 m to 775 m at about 4431 μs and from 628 m to 301 m at around 7317 μs. Fig. 2(b) also shows the light intensities of the entire channel at the time of 4431 μs and the partial channel near the tip of the stepped leader at 7317 μs are brighter than that in the preceding and following frames. The branches b_2 (at

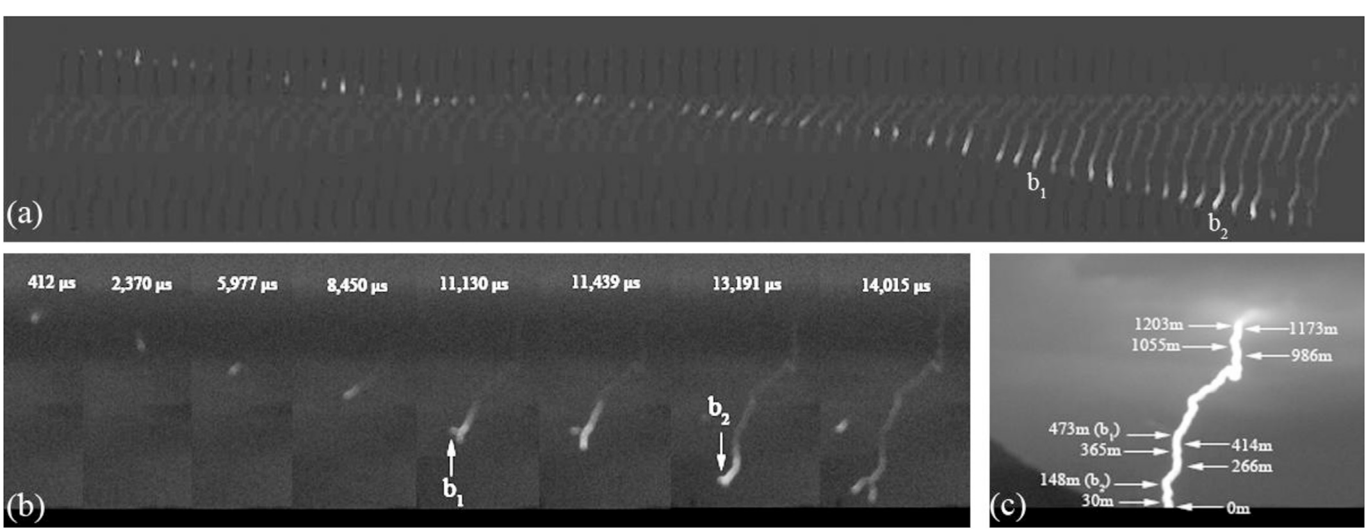

Fig. 1. Images of (a) main and (b) entire channels created by downward stepped leaders of flash A, and the sample points are marked in (c). The time markers are corresponding to abscissa in Fig. 3(a). The time interval between consecutive frames is 206 μs in (a). Each b_i symbol indicates the branches of the main channel.