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Spectral characteristics of lightning dart leader propagating in long path

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ABSTRACT

Cloud-to-ground lightning with six return strokes has been recorded with high-speed slitless spectrograph at a recording rate of 9110 frames per second. The dart leaders propagate along the same channel which consists of a long horizontal path and a vertical path, and its speed at the horizontal path is faster than that at the vertical path. The first-order spectrum of dart leader is recorded with an exposure time of 110 μs. The wavelength observed in dart leader spectrum is firstly extended to near infrared range. The spectral characteristics indicate that all the emission lines in the 400–700 nm range are radiated from singly ionized nitrogen except the H_α line at 656.3 nm, and in the range of 700–1000 nm the emission lines are radiated from neutral nitrogen and oxygen.

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1. Introduction

Lightning spectrum has been used to study the physical processes of lightning discharge for over a century (Rakov and Uman, 2003). Since 1960, the techniques of slitless spectroscopy have been applied successfully to obtain lightning spectrum, and numerous spectra were obtained (Uman and Orville, 1965). Although there are many works on the lightning spectrum (Wallace, 1960; Orville and Henderson, 1984; Weidman et al., 1989), most of them are focused on the return stroke because the leader spectrum is generally too weak to be captured. Many studies on lightning leaders (Qie and Kong, 2007; Kong et al., 2008; Zhang et al., 2009; Yoshida et al., 2012; Jiang et al., 2013) have yielded important progresses, but the spectra of lightning leaders are only reported in few literatures up to now.

Orville (1968) reported the first spectrum of stepped leader in the 560 to 660 nm range with a slitless spectrograph. The second work on stepped leader spectrum was reported forty years later. Warner et al. (2011) captured the spectrum of a cloud-to-ground (CG) lightning stepped leader at a recording rate of 10,000 frames per second (fps) in the wavelength range from 600 to 1050 nm, and the 2D speed of the stepped leader was also calculated using the OI 777.4 nm line.

The only work on spectrum of lightning dart leader has been presented by Orville (1975). The spectra of five dart leaders have been recorded by a high-speed slitless spectrograph with the time resolution of 20 μs and the exposure time of 9 μs in the range from 395 to 510 nm, and the temperature of dart leader channel was calculated to be approximately 20,000 K by singly ionized nitrogen emissions at 444.7 and 463.0 nm.

As an effective way to determine the physical parameters of lightning processes, more spectra with accurate relative intensities of spectral lines, longer wavelength range and higher wavelength resolution of lightning leaders are needed for investigation. In this paper the wavelength range of dart leader spectrum is extended to 1000 nm. Meanwhile, its propagation speeds along the horizontal path are presented based on the successive images of channel.

2. Instrumentation

The data presented in this work were from the experiment which was conducted in the summer of 2012 in Qinghai Plateau of China. The altitude of observation site is about 2530 m. The slitless spectrograph was formed by adding a plane grating with 600 lines/mm in front of a 20 mm f/2.8D lens of a high-speed camera. It has a wavelength range from 400 to 1000 nm with a wavelength resolution of about 1.1 nm (Cen et al., 2014). The camera was used to record images with recording rate of 9110 fps. It was triggered with a pre-trigger recording time of about 1 s, and the total recording times ranged around 1.8 s. Images were GPS synchronized and time stamped.

3. Results

The entire process of a cloud-to-ground lightning has been recorded at 17:06:33, 22 August 2012 (Beijing Time). The distance from the observation site to the CG lightning is about 7.14 km. The CG lightning consists of six return strokes which define as R1, R2, R3, R4, R5 and R6, respectively. Its entire duration is about 360 ms. The spectra of the six return strokes are all clearly recorded by slitless spectrograph. The light intensity of the stepped leader is too weak to be recorded. Images for channel of all dart leaders preceding subsequent return strokes are captured. Several parameters of the dart leaders are summarized in

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Table 1
Parameters of the five dart leaders. DL1 represents the dart leader that precedes return stroke R2. The same is true of DL2, DL3, DL4 and DL5. *V* stands for the propagation speed, *t* for the time interval between the beginning of the dart leader and the ending of the previous return stroke. *I* is the light intensity of the return stroke which is caused by the corresponding dart leader. It is calculated by the sum of intensity (gray value) of each pixel in the picture of return stroke channel.

Name	V (10^6 m/s)	t (ms)	I (arb.units)
DL1	4.46	59.4	4334
DL2	1.49	169.0	4244
DL3	6.11	17.8	3447
DL4	15.58	44.4	10,475
DL5	4.36	61.6	5725

Table 1. The average propagation speeds range from 10^6 to 10^7 m/s, which are close to the typical speed value of dart leader (Cooray et al., 2010). The speed of DL2 is the smallest while the corresponding interstroke interval is the longest. This result is consistent with the statistically significant tendency reporting that the lower speed of dart leader was associated with a long previous interstroke interval (Jordan et al., 1992). However, the contrary tendency could not be found in Table 1. The smallest time interval is 17.8 s, which is between R3 and DL3, but the speed of DL3 is not the maximum. DL4 has the maximum speed.

The developing process of DL1 is selected here for investigating the variation of speed. Fig. 1 presents the developing channel of the DL1 and the variation of the speed during propagation process. It can be seen from Fig. 1(a) that the entire channel can be viewed as two parts: horizontal propagation from A to B and vertical propagation from B to C. As shown in Fig. 1(b), the propagation speed of dart leader is in the order of 10^6 m/s. The speeds along the AB path are greater than the BC path, indicating that the propagation of dart leader along horizontal path is faster than that in vertical direction. In addition, the

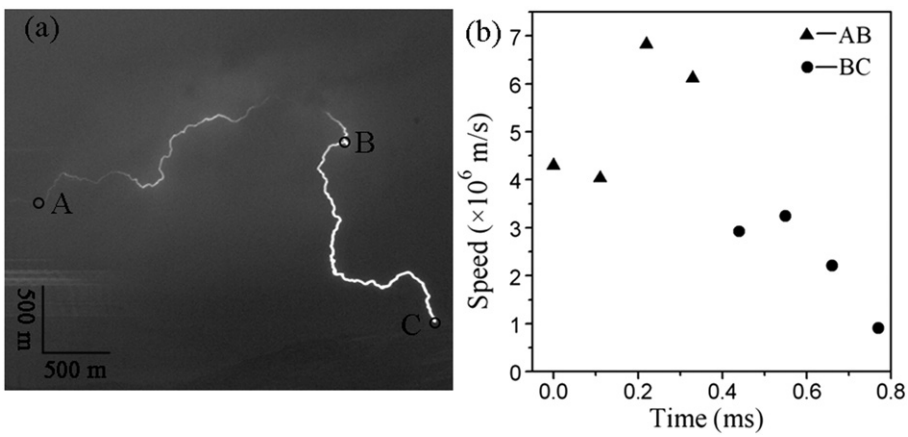

Fig. 1. (a) The entire channel developed by DL1. (b) The speed of DL1 varying with time.

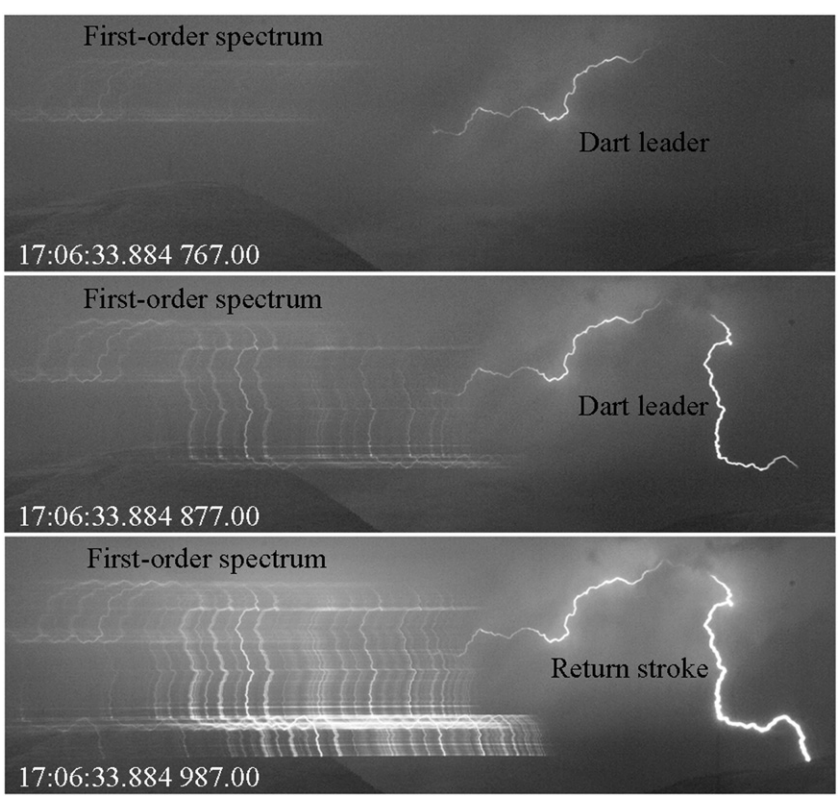

Fig. 2. Three sequential images showing the spectra of DL4 and return stroke R5.

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