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Electron density measurement of a lightning stepped leader by oxygen spectral lines

Jianyong Cen,[1] Qiang Hou,[1] Ping Yuan,[2,a] Jinjun Zhang,[1,b] Minna Sun,[1] Junxing Pan,[1] and Zengli Cao[1]
[1]*College of Physics and Information Engineering, Shanxi Normal University, Linfen, Shanxi 041000, China*
[2]*Key Laboratory of Atomic and Molecular Physics and Functional Materials of Gansu Province, College of Physics and Electronic Engineering, Northwest Normal University, Lanzhou, Gansu 730070, China*

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The time-resolved spectrum of a lightning stepped leader in downward process has been obtained by using a slitless spectrograph. Neutral oxygen and nitrogen spectral lines in the near infrared region are observed in the spectra. The electron density of the lightning stepped leader was calculated by using the Stark broadening of the oxygen spectral lines at 777.4 and 844.6 nm. The evolution characteristic of the electron density with time and channel height of the lightning stepped leader was analysed. The results shown that the electron density of the lightning stepped leader was in the order of 10^{18} cm^{-3}. The electron density decreased when the lightning stepped leader propagates downward to ground. © *2018 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* https://doi.org/10.1063/1.5042509

A stepped leader is the initial stage in lightning discharge processes and develops the channel of lightning. The formation process of a stepped leader is not fully understood.[1–4] The physical characteristics of a stepped leader in the propagation process have always been an important topic in lightning prediction.[5,6] Photographic and electrical observations[7–13] indicated that the movement of charge from cloud to ground is not continuous. The stepped leader propagates by way of a stepping process. Each step extends the length of the leader channel. The step usually appears in a microsecond and the step length ranges from several meters to hundreds of meters. The interval time between steps is about 10–200 µs. The average downward speed of a stepped leader propagating from the cloud to ground is in the order of 10^5 m/s and the total time is about 20 ms. A typical stepped leader has an average current of about 100–200 A flowing through the channel and has about 5 C of negative charge during the whole leader process. Recent reports[14–20] shown that stepped leaders can produce gamma-ray and X-ray emissions which may be directly associated with the step formation process.

Using photographic methods and electrical methods, the development speed and shape of a lightning stepped leader, and the electric field radiated from lightning stepped leader can be obtained. However, many internal physical parameters (e.g. temperature, electron density, electrical conductivity) of a lightning channel cannot be obtained by using the two methods. Analysis of the observed light emission spectra from a lightning stepped leader is an effective way to obtain the internal physical parameters.[21–26] The first spectrum of a stepped leader was recorded by using a slitless spectrograph with a wavelength range from 560 to 660 nm and time resolution of 42 µs.[27] Two singly ionized nitrogen (NII) lines at 568.0 nm and 594.2 nm, and the Hα atomic line were recorded. The temperature of the stepped leader was roughly estimated to be 30,000 K with an error of +5,000 K and -10,000 K. The second work on the spectrum of a lightning stepped leader was forty years later. Five continuous spectra of stepped leader were recorded with an exposure time of 99.6 µs each over a spectral range

[a]Electronic mail: yuanp@nwnu.edu.cn
[b]Electronic mail: zhangjinjun@sxnu.edu.cn

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from 600 to 1050 nm.[28] The spectra in the near infrared are dominated by neutral nitrogen and oxygen spectral lines. Recently, the temperature of a stepped leader was calculated by using spectra captured by a high-speed spectrograph.[29] It found that the temperature was approximately 15,000 K and it decreases during the downward propagation.

Electron density has also been a basic parameter reflecting the physical characteristics of lightning stepped leaders, which is still unknown. It is important to note that the electron density can be calculated by many different methods, but Stark broadening is rather weakly dependent on the temperature.[30] Therefore, the electron density can be determined with a good accuracy. Many spectral lines from different elements are also used to diagnose the electron density of plasmas.[31–34] In the spectra of a lightning stepped leader, the spectral lines of neutral oxygen and nitrogen are observed.[28,29] The spectral lines at 746.8, 821.6, 868.0 nm are radiated from neutral nitrogen. The three lines are not used to measure the electron density in this work. For example, there are two strong NI lines at 744.2 and 742.3 nm near the NI 746.8 nm. The profile of the NI lines at 746.8 nm may be influenced by the two strong lines. Therefore, using the oxygen spectral lines to measure the electron density of a lightning stepped leader is more reasonable.

In this study, based on the Stark broadening of the oxygen spectral lines at OI 777.4 nm and OI 844.6 nm, the electron density of the lightning stepped leader channel was obtained by using the lightning stepped leader spectra. The time evolution characteristics of electron density with the development of a stepped leader and the evolution of electron density along the channel height at the same time were also discussed, which provides a reference for further understanding the physical characteristics of a lightning stepped leader.

The data presented in this work are from an experiment which was conducted in Qinghai Plateau of China. The spectra of a lightning stepped leader were recorded by using a slitless spectrograph. The slitless spectrograph consists of a high-speed digital camera and a plane transmission grating of 600 lines mm^{-1} in front of a lens. The high-speed camera with the lens of 20 mm focal length takes black and white photos, was operated at 11,816 frames per second (fps) with an exposure time of 84.5 μs and spatial resolution of 768 × 384 pixels (each pixel is 20 × 20 μm^2 in size). The recorded spectra have a wavelength range from 400 to 1000 nm with a wavelength resolution of 1.04 nm.[35]

The entire process of a lightning stepped leader has been recorded by the slitless spectrograph. The original spectra are digital pictures of the whole discharge channel outside the cloud. Four pictures are captured in the stepped leader process before the occurrence of first return stroke. The original images of the stepped leader and return stroke are shown in Fig. 1. The time of return stroke is denoted as 0 μs. Due to the stepped leader happening before the return stroke, the four spectra of the stepped leader are denoted as -338 μs, -253.5 μs, -169 μs, and -84.5 μs, respectively.

The tip of the stepped leader channel in each image was selected for quantitative analysis. The images are transformed into spectral graphs which are represented by the relative intensity distributions of lines. The spectral graphs of the stepped leader and the following return stroke are given in Fig. 2. The abscissa represents the wavelength in nanometer and the vertical ordinate represents the relative intensity of spectral lines.

As shown in Fig. 2, in the spectrum of return stroke at 0 μs, most of the spectral lines are radiated from NII except the Hα line in the visible range (400-700 nm). In the near-infrared range (700-900 nm), the spectral lines are radiated by neutral nitrogen and oxygen. However, in the spectra of the stepped leader at -338 μs, -253.5 μs, -169 μs, and -84.5 μs, the spectral lines of NII almost disappear, only remains the neutral oxygen and nitrogen spectral lines in the near-infrared range. The spectral lines of OI at 777.4, 844.6 nm and NI at 746.8, 821.6, 868.0 nm can be observed at every moment in the spectra of stepped leader. The OI 777.4 nm is persistent and strongest line among these spectral lines. The NII spectral lines are present in the return stroke but not in the stepped leaders, which can be explained as follows. The stepped leader is a weakly discharge process and has the current of about 100–200 A flowing through the channel. The NI and OI spectral lines with relatively low excitation energies are excited from the discharge channel. The return stroke is the strongest discharge process and has the peak current of about 10^4–10^5 A flowing through the discharge channel. Thus, the NII spectral lines with relatively higher excitation energies can be excited.

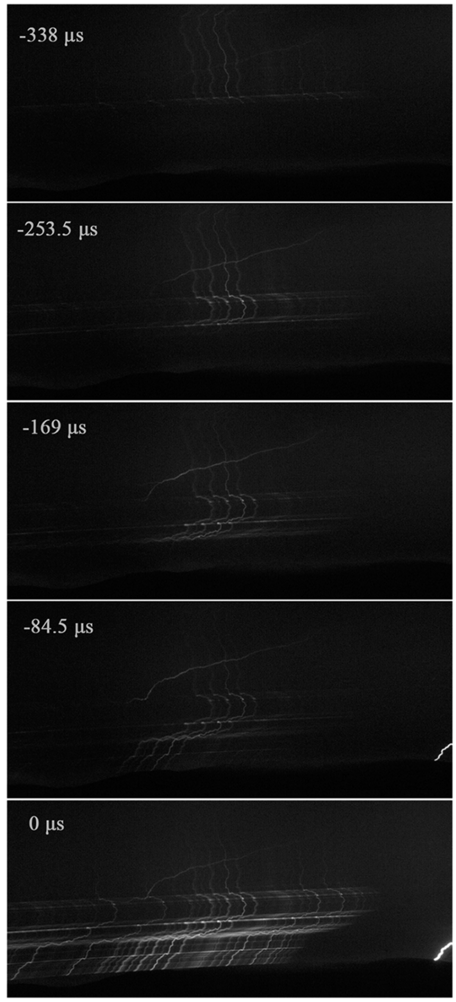

FIG. 1. The original images showing the spectra of stepped leader (-338 μs, -253.5 μs, -169 μs, and -84.5 μs) and return stroke (0 μs).

Using the spectral information to calculate the corresponding parameter of the lightning discharge plasma, two assumptions are usually needed: (1) The discharge channel is optically thin. (2) The channel is in local thermodynamic equilibrium (LTE). The validity of the assumptions has been proved by previous works.[36,37] Under the condition of LTE, and when the electron density $n_e \geq 10^{15}$ cm^{-3}, the contributions by other broadening mechanisms (Doppler broadening, resonance pressure broadening, instrumental broadening, etc.) can be neglected compared with the Stark effect.[38,39] The full width at half maximum of lines $\Delta\lambda_{1/2}$ is related to the electron density n_e with the following equation[30,40]

$$\Delta\lambda_{1/2} = 2\omega\left(\frac{n_e}{10^{16}}\right) \tag{1}$$

where ω is the electron impact width parameter or Stark width parameter, can be obtained from the reference data.[41]

In the present study, the spectral lines of OI at 777.4 and 844.6 nm are used to derive the electron density, respectively. According to Equation (1), it is found that the electron density of the lightning stepped leader is in the order of 10^{18} cm^{-3}. The variation of the electron density at different times is shown in Fig. 3. The electron density of the stepped leader at the four different times is calculated by both the OI 777.4 nm and OI 844.6 nm. At -338 μs, the stepped leader is far away from the ground and the electron density is about 3.3×10^{18} cm^{-3} corresponding to the biggest value of all. As time going, the stepped leader is getting closer and closer to the ground. When the stepped leader

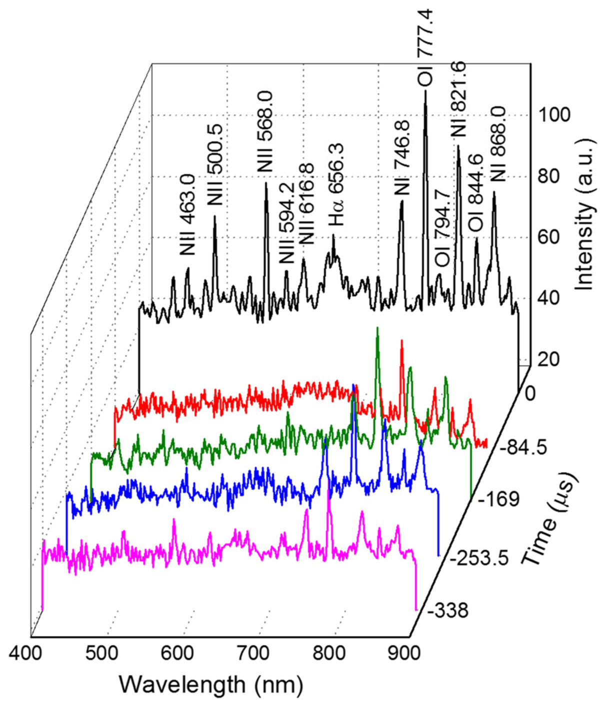

FIG. 2. Spectral graphs of lightning stepped leader (-338 μs, -253.5 μs, -169 μs, and -84.5 μs) and return stroke (0 μs).

propagates to the closest position of the ground at -84.5 μs, the electron density reduces nearly in half. In other words, the electron density decrease as the lightning stepped leader propagates downward to ground. Moreover, the electron density of the return stroke is also calculated. The electron density is 5.87×10^{18} cm^{-3} calculated by the OI 777.4 nm for the return stroke. And the electron density is 5.69×10^{18} cm^{-3} by using the spectral line of OI 844.6 nm.

Comparison of the electron density determined from OI 777.4 nm and OI 844.6 nm is shown in Fig. 4. The value of the electron density measured by OI 777.4 nm is slightly greater than the value measured by OI 844.6 nm, but the electron density plot shows good linearity by both spectral lines. It also proves that the electron density measurement by these two oxygen spectral lines is reliable.

The stepped leader has the longest channel at -84.5 μs. The electron density at each point in the channel can be calculated. Fig. 5 shows the variation of the electron density along the channel height

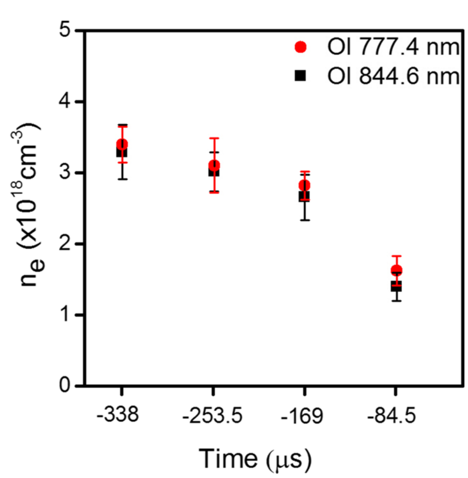

FIG. 3. Variation of the electron density measured from OI 777.4 nm and OI 844.6 nm at different times.

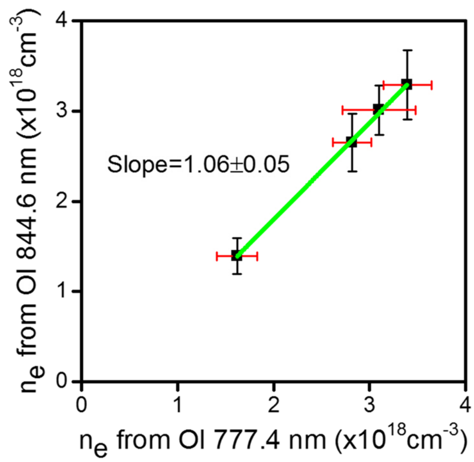

FIG. 4. Electron density plot measured from both OI 777.4 nm and OI 844.6 nm.

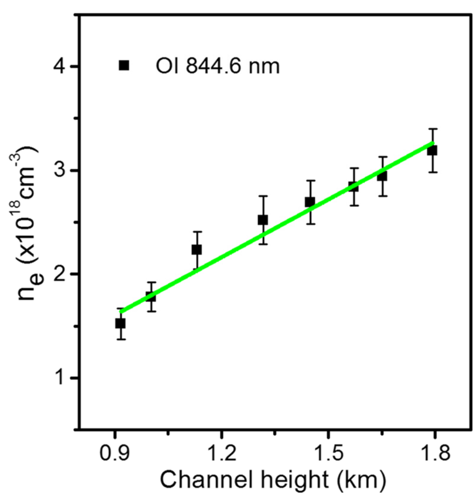

FIG. 5. Variation of the electron density along the channel height of stepped leader at -84.5 μs.

by using the OI 844.6 nm. The height of the ground is defined as 0 km. The electron density is about 3.2×10^{18} cm^{-3} at the channel position of 1.8 km above the ground. At the channel height of 0.9 km corresponding to the closest channel position to the ground, the electron density is 1.52×10^{18} cm^{-3}. The electron density decreases when the channel height is close to the ground. It also can be found that the electron density decreases linearly with the reduction of channel height.

The electron density of the return stroke is 5.69×10^{18} cm^{-3} which is in accordance with the previous reports.[42,43] The electron density of the stepped leader ranges from 1.5×10^{18} to 3.3×10^{18} cm^{-3}, which is about one quarter to one half of the electron density of the return stroke. The temperature of the return stroke is usually more than 25000 K,[23] but the temperature of the stepped leader is around 15000 K.[29] These indicate that the stepped leader has a weak ionization process with relatively low electron density and temperature in the plasma channel.

In summary, the time-resolved spectra, recorded by high-speed slitless spectrograph, have been applied to study the electron density of a lightning stepped leader. The electron density is obtained by using the oxygen spectral lines. The electron density of the lightning stepped leader is in the order of 10^{18} cm^{-3}. The evolution characteristics show that the electron density decreases as the stepped leader propagates downward to ground. Meanwhile, the electron density also decreases with the reduction of channel height. The study can provide some reference data for revealing the formation process of stepped leaders and simulating lightning discharges in laboratory.

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