Journal of Atmospheric and Solar–Terrestrial Physics 159 (2017) 41–47

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar–Terrestrial Physics

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

Variation of the channel temperature in the transmission of lightning leader

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ARTICLE INFO

Keywords:
Lightning spectrum
Stepped leader
Dart leader
Channel temperature

ABSTRACT

According to the time-resolved spectra of the lightning stepped leader and dart leader processes, the channel temperature, its evolution characteristics with time and the variation along the channel height in the transmission process were analyzed. The results show that the stepped leader tip has a slightly higher temperature than the trailing end, which should be caused by a large amount of electric charges on the leader tip. In addition, both temperature and brightness are enhanced at the position of the channel node. The dart leader has a higher channel temperature than the stepped leader but a lower temperature than the return stroke. Meanwhile, the channel temperature of the dart leader obviously increases when the dart leader propagates to the ground.

1. Introduction

The large current and strong electromagnetic radiations caused by lightning discharge are the main causes of lightning disasters (Soriano et al., 2005). The powerful return stroke current can heat the discharge channel to tens of thousands of degrees and form a plasma channel. The thermodynamic properties of the lightning plasma channel are the theoretical basis of lightning protection and early warning (Wang et al., 2012). The temperature is a basic parameter used to describe the physical characteristics of a lightning discharge channel (Li et al., 2012; Nakimana et al., 2013; Lu et al., 1994). The investigation of the channel temperature and conductive properties in the development of the lightning leader is important to reveal the physical mechanism of lightning occurrence.

Spectral analysis is an effective way to diagnose the channel temperature of lightning discharge. It is difficult to obtain the lightning leader spectrum because the radiation of the lightning leader channel is relatively weak, and the channel luminosity will significantly weaken after light splitting by the grating. Currently, there are few reports on the lightning leader spectrum. Orville (1968) first photographed a lightning leader spectrum with a slitless spectrometer, because the recorded wavelength range was only 560–660 nm, he estimated the channel temperature using two recorded NII lines (NII 568.0 nm and NII 594.2 nm). Orville (1975) also recorded the dart leader spectra, whose wavelength range is 398–510 nm, and estimated the temperature of the dart leader channel with NII 444.7 nm and NII 463.0 nm. Warner et al. (2011) first used a high-speed video camera as a recording system to extend the recorded wavelength range of the lightning stepped leader to 600–1050 nm. Cen et al. (2015) recorded the spectra of the lightning dart leader in the wavelength range of 400–1000 nm and qualitatively analyzed the evolution of the channel temperature by the intensity variation of the spectral lines during the dart leader transferred to the ground. Presently, we still require a large amount of data about the channel temperature and evolutionary characteristics in the transmission process of the lightning leader. In this paper, the channel temperature and conductivity were calculated using the spectra of the CG lightning leader. Moreover, the changes of these parameters with time and along the channel height were analyzed.

2. Theoretical methods

2.1. Channel temperature

To calculate the physical parameters of the lightning channel according to the spectral information, two basic assumptions must be satisfied: 1) the channel is optically thin; 2) the channel is in local thermodynamic equilibrium (LTE). Uman and Orville (1965) confirmed that the lightning discharge channel was optically thin for the spectral lines of NII, OI, NI and H_α. Griem (1964) proved that the lightning channel satisfied the local thermodynamic equilibrium. Under the LTE condition, the channel temperature (Uman and Orville, 1965) and transition parameters of spectral lines satisfy the following formula:

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http://dx.doi.org/10.1016/j.jastp.2017.04.006
Received 11 January 2017; Received in revised form 28 March 2017; Accepted 19 April 2017
Available online 10 May 2017
1364-6826/

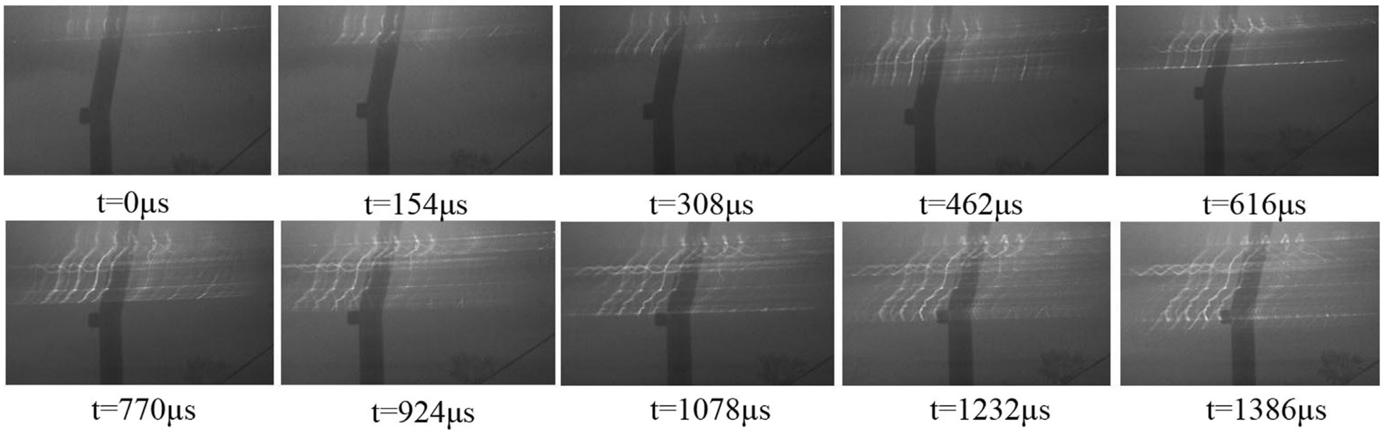

Fig. 1. Original spectrogram of a lightning stepped leader channel.

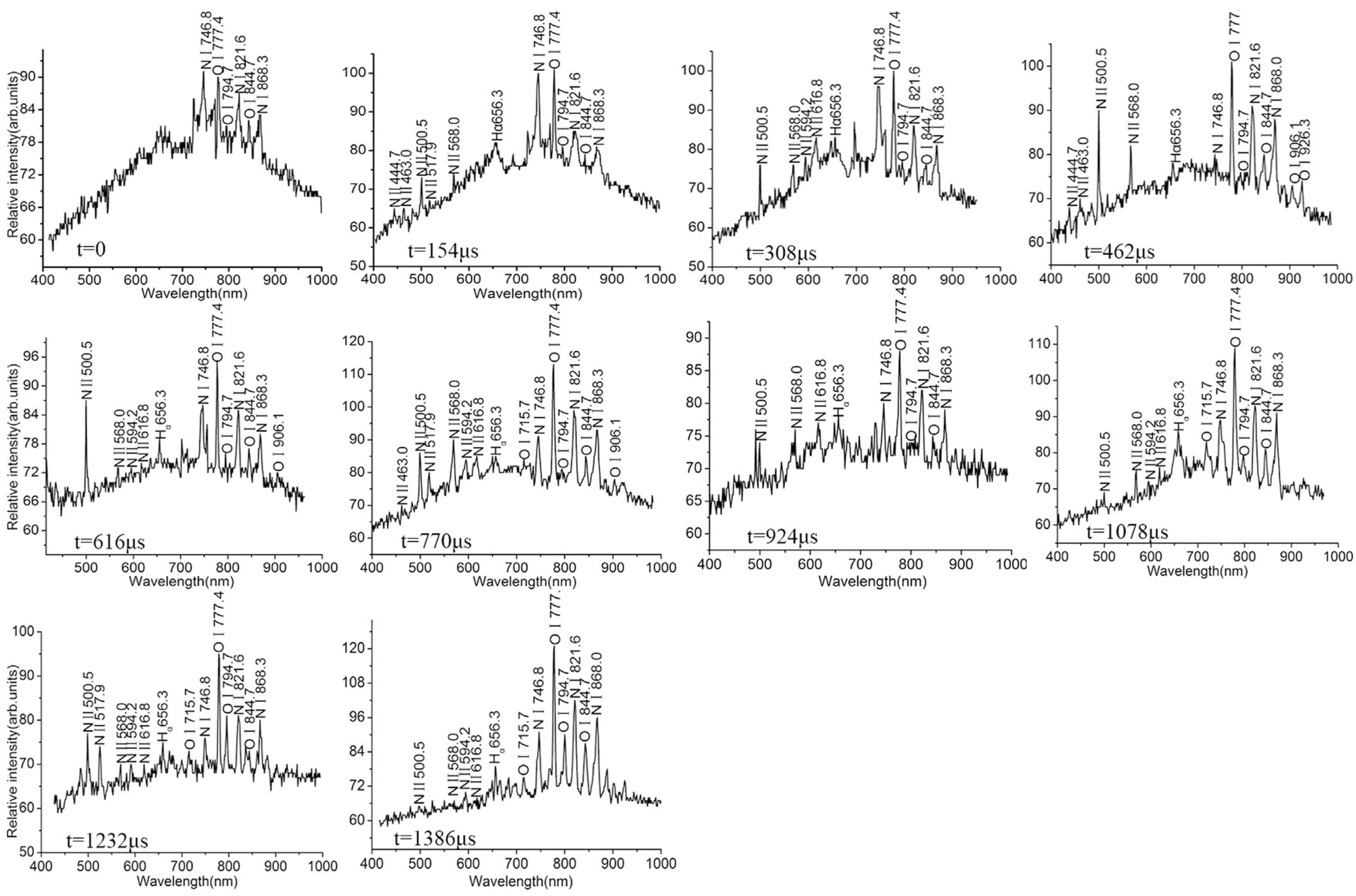

Fig. 2. Spectrum of the stepped leader tip expressed in the relative intensity of spectral lines.

$$\ln\left(\frac{I\lambda}{gA}\right) = -\frac{E}{kT} + c \tag{1}$$

where C is a constant, I is the relative intensity of spectral lines, λ is the transition wavelength, g is the statistical weight, A is the transition probability, E is the upper excitation energy, k is the Boltzmann constant, and T is the temperature. We select multiple spectral lines of atoms or ions of the same category. Then, we fit a straight line by taking E as the horizontal coordinate and the value of $\ln(I\lambda/gA)$ as the vertical coordinate. The temperature is obtained from the slope of the straight line.

2.2. Electron density

Under the LTE approximation, neutral atoms and charged ions satisfy the Saha distribution, the electron density of the lightning channel satisfies the Saha equation (Qiu, 2002):

$$Ne = 4.83 \times 10^{15}\left(\frac{I_a}{I_i}\right)\left(\frac{gA}{\lambda}\right)_i\left(\frac{\lambda}{gA}\right)_a T^{3/2}10^{-5040(V+E_i-E_a)/T} \tag{2}$$

where I_a and I_i are the intensities of neutral atoms and singly ionized atoms (arb. units), respectively, E_a and E_i are the upper-level energies of the atomic and ionic lines (eV), respectively, and V *is* the ionization energy (eV).