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Temperature distribution and evolution characteristic in lightning return stroke channel

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ABSTRACT

According to the time-resolved spectra of four lightning return strokes, the temperatures of arc core channel and the peripheral optical channel surrounding the arc core are investigated by different methods; the temperature distribution along the radial direction of channel on the peak current stage is discussed. The results show that a temperature gradient is formed along the radial direction of channel during the discharge process. With the increasing of the radius, the temperature decreases gradually. The temperature of arc core channel is about 4000–5000 K higher than that of the peripheral optical channel. The time evolution of channel temperature shows that the falling of the temperature is very slow compared with the decreasing of the current after their peak values. After the peak current, the channel temperature is still maintained at around 20,000 K up to 200–400 μs. The heat effect resulting from such a long-time high temperature is the main source of most direct lightning disasters.

1. Introduction

The instantaneous strong current in lightning discharge process forms a plasma channel of about 30,000 K. The high temperature of discharge channel and its heat effect are the main causes of forest fire, power transmission system damage and many other direct lightning disasters (Soriano et al., 2005; Kong et al., 2015). Therefore, the temperature of lightning return stroke channel and its evolution characteristic has been an issue of concern in the area of lightning protection and research. Spectral diagnostics of plasma is an effective way to obtain the temperature of discharge channel. Orville (1968a, 1968b) and Uman (1969a) calculated the channel temperature by lightning spectra at the earliest. Cen et al. (2011) obtained the temperature of return stroke channel and discussed the correlation between temperature and action integral of the current. Due to the limitation on time resolution and photosensitive range of spectrograph, it was difficult to get the lightning spectra with high time resolution and wide wavelength range in the past. Most of the works on the temperature of lightning return stroke channel were based on the time-integral spectra of return stroke stage. And the spectra of visible and infrared range were observed separately. The only work on time-resolved spectra of lightning was reported by Orville (1968b), which studied the evolution of channel temperature during the initial 50 μs of return stroke process. The evolution characteristic and distribution along the radial direction of channel temperature during return stroke process are closely related to the energy and heat transfer of lightning process, there are few works on this respect up to now.

In this paper, using the spectra of lightning return stroke process obtained by high-speed spectrograph in the range of 400–1000 nm, different methods are adopted to diagnose the temperature of the discharge channel. The analysis of distribution and evolution characteristic of the temperature in return stroke process would provide reference data for further researches on heat and energy transmission of return stroke channel and lightning protection.

2. Theoretical methods

Using the spectral information to calculate the physical parameters of lightning channel, two basic assumptions must be met: 1) The channel is optically thin; 2) The channel is in local thermodynamic equilibrium (LTE). Uman and Orville (1965) investigated the time-integrated lightning spectra and authenticated that the discharge channel was optically thin for NII, OI, NI and Hα. In addition, Uman (1969b) indicated that the quasi equilibration time for NII lines and that for electron and ion kinetic energies in the lightning return stroke channel is on the order of 0.01 μs. So, the local thermodynamic equilibrium is achieved within the lightning channel in a short time compared with that in which the parameters of the channel change. Under above two basic assumptions, then the temperature, electron density and the

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temperature distribution along the radial direction can be obtained by methods as follow.

2.1. Multiple-line method

When multiple lines of same element can be recorded in lightning spectra, the multiple-line method is the most common way to diagnose the channel temperature (Cen et al., 2011).

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

where I is the relative intensity of spectral line (arbitrary unit, a.u.), λ is the wavelength (nm), g, A, and E are the statistical weight, transition probability, and upper excitation energy of corresponding transition (eV), respectively. k is Boltzmann constant, c is the constant, T is the temperature (K). Fitting straight line with $\ln(I\lambda/gA)$ as vertical coordinate and E as abscissa, then the temperature can be calculated through the slope parameter $(-1/kT)$.

In the case of less observable spectral line, the Stark broadening of certain spectral line can be used to estimate the electron density, and then the Saha equation which reflects the correlation between electron density and temperature is used to derive the channel temperature.

2.2. Stark broadening

In the LTE condition, the relationship between Stark broadening of Hα 656.3 nm and electron density is given as following (Gigosos et al., 2003)

$$\Delta\lambda_{1/2} = 0.549 \times \left(\frac{N_e}{10^{17}\ \mathrm{cm}^{-3}}\right)^{0.67956} \tag{2}$$

where $\Delta\lambda_{1/2}$ is the full width at half maximum (FWHM) (nm), N_e is electron density (cm^{-3}).

Semi-empirical formula (Hegazy, 2010) for broadening of neutral oxygen lines is

$$\Delta\lambda_{1/2} = 2\omega\left(\frac{N_e}{10^{16}}\right) \tag{3}$$

where ω is the broadening parameter (Griem, 1974).

2.3. Saha equation

Under the LTE approximation, the charged ions and the neutral atoms satisfy Saha distribution. There are mainly the neutral atoms and singly ionized atoms with lower excited levels in lightning channel. For lower ionization levels, the electron density is calculated approximately by Saha equation (Qiu, 2001)

$$N_e = 4.83 \times 10^{15}\left(\frac{I_a}{I_i}\right)\left(\frac{gA}{\lambda}\right)_i\left(\frac{\lambda}{gA}\right)_a T^{3/2}10^{-5040(V+E_i-E_a)/T} \tag{4}$$

where I_a and I_i are the intensity of lines for neutral atoms and singly ionized atoms (a.u.). E_a and E_i are the upper-level energy of atomic lines and ionic lines (eV). V is the ionization energy (eV).

2.4. Temperature distribution

Heat conduction and diffusion along the radial direction are the main ways reducing the temperature of lightning channel. Due to the tiny difference in temperature along the axis, the lightning channel can be regarded as an axial uniform cylinder. In addition, the thermal conductivity almost remains unchanged within the range of radius discussed. If the convection between air in channel and the surrounding is neglected, the radial heat conduction is considered only; it can be regarded as one-dimensional steady heat conduction. On the basis of Fourier heat conduction law combined with energy conservation and their transfer rate equation, the heat conduction differential equation under the cylindrical coordinate system is given by

$$\frac{1}{r}\frac{d}{dr}\left(\lambda r\frac{dT}{dr}\right) = 0 \tag{5}$$

The boundary conditions are introduced to solve the differential Eq. (5), and then the distribution of channel temperature along the radial direction can be obtained.

3. Instrumentation and discussion

3.1. Instrumentation

The time-resolved spectra of four lightning return stroke processes are captured by a slit-less dynamic high-speed spectrograph in the wavelength range of 400–1000 nm with a wavelength resolution of about 1.1 nm (Cen et al., 2014), the recording system of the spectrograph is a high-speed video camera with recording speed of 9110–13,880 fps. A transmission grating of 600 lines mm^{-1} is put in front of the object lens of the camera.

3.2. Results and discussion

The original spectra are digital pictures of the whole discharge channel outside the cloud during the return stroke process. Based on the shape of channel and the spectral resolution quality, excellent positions along the channel are selected, and the pictures are transformed into spectral graphs, which are represented by the relative intensity distributions of lines. The spectra at a typical position are given in Fig. 1, which corresponding to the decay stage of return stroke current. For convenience, the four return strokes are marked as A, B, C and D, respectively. Five clear spectra are recorded for each return stroke process. The time corresponding to the first spectrum of each return stroke is defined as 0. The light of return strokes A, C and D lasted for about 440 μs, while that of the return stroke B lighted for 288 μs. It can be seen in Fig. 1, with the evolution of time, that the spectral structure changes obviously during return stroke process. Intense lines of NII appear only at the initial stage of return stroke process, then the intensity of ionic lines decreases rapidly. In addition, in the near-infrared region, the neutral emission lines can be clearly recorded in the whole return stroke process. The evolution law of the spectral structure is closely related to the variation of the discharge current.

The upper excitation energy of the neutral emissions from OI and NI is 10–14 eV, while that of NII lines is 20–30 eV. It can be inferred from the spectral structure and corresponding excitation energy that the neutral and ionic lines should be the radiation from different position along the radius of the discharge channel. The ionic lines which are observable mainly at the initial stage of return stroke process are from the arc core channel, and the neutral emissions should be mainly the radiation of the peripheral optical channel. The study on the diameter of lightning discharge channel also demonstrated that the visual diameter (defined according to the luminous range, namely the optical diameter) from optical observation is far greater than that of the arc core channel (Golde, 1981). Hence the temperature calculated by NII lines should reflect the condition of arc core channel (Orville and Henderson, 1984).

In order to further analyze the physical characteristics in the discharge process, the channel temperature and its evolution characteristic are calculated by different methods. According to the intensity and the transition parameters of several NII lines, the