Calculating the electron temperature in the lightning channel by continuous spectrum

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Abstract

Based on the theory of plasma continuous radiation, the relationship between the emission intensity of bremsstrahlung and recombination radiation and the plasma electron temperature is obtained. During the development process of a return stroke of ground flash, the intensity of continuous radiation spectrum is separated on the basis of the spectrums with obviously different luminous intensity at two moments. The electron temperature of the lightning discharge channel is obtained through the curve fitting of the continuous spectrum intensity. It is found that electron temperature increases with the increase of wavelength and begins to reduce after the peak. The peak temperature of the two spectra is close to 25000 K. To be compared with the result of discrete spectrum, the electron temperature is fitted by the O I line and N II line of the spectrum respectively. The comparison shows that the high temperature value is in good agreement with the temperature of the lightning core current channel obtained from the ion line information, and the low temperature at the high band closes to the calculation result of the atomic line, at a low band is lower than the calculation of the atomic line, which reflects the temperature of the luminous channel of the outer corona.

Keywords: lightning spectrum, plasma continuous radiation, spectral separation, electron temperature

(Some figures may appear in colour only in the online journal)

1. Introduction

It is difficult to study the physical properties of the lightning discharge channel due to the thunder and lightning happening randomly and transiently. The physical properties of the lightning discharge channel can be obtained through the observation and analysis of the lightning spectra. Lightning discharge channels belong to thermal plasma, and the electron temperature is one of the basic parameters of plasma properties [1]. The electron temperature of the natural lightning channel is obtained from the spectral information [2, 3]. The computation method is mainly using the double-line and multispectral method of the characteristic spectral lines computation; however, the result from double-line method is sensitive to the parameter changes of spectral lines, and is not stable. Therefore, the multispectral method becomes a commonly used method to calculate the electronic temperature of the lightning discharge channels.

Compared with the laser induced plasma spectrum, the lightning spectral continuous radiation, mainly from bremsstrahlung and recombination radiation, is more remarkable [4]. Through the analysis of lots of lightning spectrum, it can be seen that the relative intensity of the continuous radiation changes with wavelengths, and forms a continuous distribution, the reason why the short-wave band to the long-wave band increased first and then reduced is that the total emission coefficient of the plasma continuous spectrum is the function of temperature and wavelength [5]. So the temperature of lightning discharge channels can be diagnosed by using a continuous spectrum. Previously the diagnosis of the electron temperature of lightning channels was conducted based on a discrete
spectrum. This paper attempts to diagnose the temperature by using the continuous spectrum for comparison with the diagnostic results of discrete spectra.

2. Theoretical methods

2.1. The excitation mechanism of continuous radiation

The temperature in the channel can reach \(10^4\) K magnitude in the process of lightning discharge, and molecules are fully dissociated, so the molecular radiation can be ignored; Usually the lightning spectrum is obtained at night or in the black environment, so the continuous radiation caused by the stray light is very weak, which can also be ignored. Thus the recombination radiation and bremsstrahlung radiation is the main source of continuous radiation, namely, the interaction between moving electrons and particles. The mechanism can be expressed by the following formula (6)

\[
\begin{align}
M^n + e(HV) &\rightarrow M^n + e(LV) + k\hbar\nu \\
M^{n+1} + e(HV) &\rightarrow M^n + k\hbar\nu \\
M^{n+1} + M^{-1} &\rightarrow M^n + k\hbar\nu
\end{align}
\]

where \(n = 0, +1, +2, \ldots\) corresponding, \(M^0, M^{+1}, M^{+2} \ldots\) respectively represent the atom, ion valence 1 and ion valence 2 \(\ldots\). \(M^{-1}\) stands for anion. Formula (1) corresponds to the bremsstrahlung, which is the interaction between high-velocity electrons and heavy particles. In the process of collision free-free state transition occurred, when \(k = 0\), producing energy transfer; when \(k = 1, 2, \ldots\), producing multiple-photon radiation. Formulae (2) and (3) stand for the process of recombination radiation, the transition of free-bound state and bound-bound state happening [7], electrons captured by the ion, or the positive and negative ions directed to the recombination radiation, and the energy released in the form of photons. The electron-electron collision which has little effect on radiation will not be considered in this paper.

2.2. The relationship between continuous radiation intensity and electron temperature

Consider bremsstrahlung first. Suppose electrons subject to the Maxwell speed distribution. In the binary collision the bremsstrahlung emission energy can be written as [8–11]

\[
\varepsilon(v) = n_e n_i Z^2 \left( \frac{e^2}{4\pi\varepsilon_0} \right)^3 \frac{8\pi}{3\sqrt{3} m_e c^3} \times \left( \frac{2m}{\pi T_e} \right) e^{-\frac{hv}{kT_e}}.
\]

In the formula \(n_e\) stands for electron concentration, \(n_i\) for ion concentration, \(g_{ff}\) for the function containing Gaunt factor. About the recombination radiation, there is

\[
\varepsilon(v) = n_e n_i Z^2 \left( \frac{e^2}{4\pi\varepsilon_0} \right)^3 \frac{8\pi}{3\sqrt{3} m_e c^3} \times \left( \frac{2m}{\pi T_e} \right) \\
\times e^{-\frac{hv}{kT_e}} Z^2R_e^2 \frac{2}{T_e} G_0 e^{\pi T_e/kT_e}.
\]

Among them, \(R_0 = (e^2/4\pi\varepsilon_0\hbar)^2 = 13.6\) eV stands for the Rydberg energy.

Formula (5) is the hydrogenlike approximation results in need of non-hydrogenlike approximation correction. Because in the lowest incomplete shell at most accommodates \(2n^2\) electrons rather than \(2n^2\). The probability of the recombination radiation decreases according with \(\xi/2n^2\), and the precise ionization energy \(\chi_i\) replaces the hydrogenlike approximation \(Z^2R_e/n^2\). Formula (5) will be extended for two: the first describes the recombination radiation corresponding to the lowest electron shell, and the second describes the recombination radiation corresponding to all the other shells than the lowest electron shell. The total energy of the continuous radiation is expressed as [8–11]

\[
\varepsilon(v) = n_e n_i Z^2 \left( \frac{e^2}{4\pi\varepsilon_0} \right)^3 \frac{8\pi}{3\sqrt{3} m_e c^3} \times \left( \frac{2m}{\pi T_e} \right) \\
\times \left( g_{ff} + G_0 \frac{\xi_i}{n^2 \frac{T_e}{m}} \right) e^{-\frac{hv}{kT_e}} \\
+ \sum_{r=n+1}^{\infty} G_0 \frac{Z^2R_e^2}{T_e} \frac{2}{n^2} G_0 e^{\pi T_e/kT_e}.
\]

The first item corresponds to the bremsstrahlung, the second corresponds to the recombination radiation at the lowest incomplete shell, and the third corresponds to the recombination radiation at the other shells. Usually there is \(hv \gg Z^2R_e/n^2\), \(G_0 = 1\); \(hv < Z^2R_e/n^2\), \(G_0 = 0\). As can be seen from the above, the continuous radiation energy is related to the plasma density and temperature, but the shape of a continuous spectrum is mainly determined by the electron temperature. Therefore the shape of a continuous spectrum can be used to diagnose the electron temperature of the plasma.

Take natural logarithm on both sides of formula (6), there is

\[
\ln(\varepsilon(v)) \propto -\frac{hv}{T_e}.
\]

It is observed that the natural logarithm of the spectrum intensity of the continuous radiation is approximately proportional to the
energy of the photons, and the negative value of its slope is the reciprocal of the electron temperature.

3. Data analysis

3.1. Continuous spectrum method to calculate the electron temperature in the channel

Figure 1 shows a cloud-to-ground flash discharge spectrum in Qinghai area in 2015. Figures 1(a) and (b) are the two original spectra from the same lighting return stroke process, with a time interval of 117 microseconds; figure 1(a) corresponds to the peak current stage. As can be seen from the lightning photos, the flash of figure 1(a) is stronger than that of figure 1(b). The spectrum is obtained by the non-slit grating spectrograph that is configured with 600 per mm transmission grating spectrum [12]. The non-slit grating spectrograph with 3CCD records, whose spectral response range is 400–1000 nm. Figure 2 shows the spectrogram expressed with relative intensity after the spectrum identification.

In accordance with the direction of wavelength increasing, we extract the lowest point of the spectrum of figure 2, and obtain the distribution characteristics of the relative intensity of the continuous radiation according to the wavelength expanding, get the shape and intensity of a continuous spectrum. In the process of extraction the unobvious area of line spectrum should be chosen to exclude the interference of line spectrum, which is shown in figure 3.

The kinetic energy of the electrons in the lightning plasma shows a distribution from low to high energy [13]. When the photon energy of the continuous spectrum generated by the electrons through bremsstrahlung and recombination radiation \( h\nu < Z^2R_e/n^2 \), \( G_0 = 0 \), and there is no recombination radiation. The relative strength \( \varepsilon(\nu) \) of spectrum changes continuously with \( -h\nu \), as shown in figure 3. When the photon energy of the continuous spectrum \( h\nu > Z^2R_e/n^2 \), the relative strength \( \varepsilon(\nu) \) of spectrum changes continuously with \( -h\nu + Z^2R_e/n^2 \); near \( h\nu = Z^2R_e/n^2 \) an inflection point is formed, corresponding to the position of the inflection point of the relative strength of the continuous spectrum, from which we can see that the inflection point is due to the competition existing on the frequency band between bremsstrahlung and recombination radiation. For the convenience of using formula (7) to fit the temperature, the abscissa by wavelength in figure 3 is converted into that by energy with the unit of eV, the ordinate converted to \( -\ln \varepsilon(\nu) \), as shown in figure 4. Near \( h\nu = Z^2R_e/n^2 \) the error of formula (7) is
becoming bigger, so fitting temperature is unfavorable. Thus the inflection point is regarded as the center, the temperature fitting is divided into high and low energy area respectively. In the process of fitting attention should be paid to the shape distortion of the continuous spectrum brought by the spectral absorption [14]. Considering the continuous changes of the temperature along the radial channel, the temperature fitting is proposed to carry on with the inflection point of continuous spectrum as the center extending to the high-energy and low-energy area respectively for piecewise fitting. The piecewise fitting line is shown in figure 4. The parameters and the results of temperature calculation are listed in table 1, of which $T$ is kinetic temperature of the plasma, the fitting result of formula (7), $T_e$ for the corresponding plasma temperature.

### 3.2. The electron temperature of channel calculated by characteristic spectrum

The lightning spectrum has lots of strong ion lines and atomic lines, of which the N II line and O I line are fairly rich. In order to verify the calculation results of the continuous spectrum, the multispectral slope method is used to fit the plasma temperature [15–17], which is a commonly used method to diagnose the lightning plasma temperature by discrete spectrum, discussed in the literature, as shown in formula (8)

$$\ln \left( \frac{I_\lambda}{gf} \right) = - \frac{E_p}{kT_e} + C. \quad (8)$$

$I$ is for the relative intensity of the spectral lines, $\lambda$ for spectrum wavelength, $g$ for the statistical weight of the upper excitation level, $f$ for oscillator strength, $E_p$ as upper excitation level, $E_p$ and $gf$ can be checked from the NIST database.

The intensity N II and O I of the discrete spectrum can be obtained from figure 2. Choosing N II 518.0 nm, N II 594.2 nm, N II 616.7 nm, N II 648.2 nm as a group, O I 715.7 nm, O I 777.2 nm, O I 844.6 nm and O I 926.6 nm for another group, respectively using formula (8) for linear fitting, the result is listed in table 1.

It is observed that the electron temperature of the lightning channel has a lower limit, the lower temperature limit related to the development process of plasma. At the two moments of return stroke the minimum temperatures are 6300 K and 4300 K respectively calculated by the continuous spectrum, showing obvious temperature difference; but the electron temperature difference is not obvious at the parts of high temperature at the two moments of lightning return stroke. Studying the radiation characteristics of the lightning channels shows that [18], the lightning channels should contain the core current channel of high temperature and the luminous channel of outer corona, and

### Table 1. Results of the electron temperature of the lightning discharge channel.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Based on continuous spectrum</th>
<th>Based on characteristic spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E$(eV)</td>
<td>$T$(eV)</td>
</tr>
<tr>
<td>a</td>
<td>1.42–1.56</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>1.56–1.76</td>
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<td></td>
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<tr>
<td></td>
<td>1.27–1.41</td>
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<td></td>
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<tr>
<td></td>
<td>2.78–2.41</td>
<td>2.18</td>
</tr>
<tr>
<td></td>
<td>2.88–2.58</td>
<td>2.04</td>
</tr>
</tbody>
</table>

Figure 4. Fitting results of continuous spectrum.
that in the spectral radiation the ion line of higher excitation energy mainly comes from the core channel. Table 1 shows that the temperature value made by the N II line accords well with the results of the continuous spectrum in the high-energy region; while the temperature value from atomic spectral lines close to the results of the continuous spectrum in the high-energy region. Therefore, the temperature on the basis of the calculation of the continuous radiation spectrum can more reasonably reflect the temperature characteristics of different areas in the plasma environment. Based on this method, it is expected to further analyze the temperature distribution and energy-storage characteristics along the lightning channel radial.

4. Conclusion

Using the continuous spectrum to calculate the electron temperature in the lightning discharge channels at the different moments of a back flash demonstrates that the electron temperature near the inflection point of the continuous spectrum intensity is consistent with the results obtained through the ion spectrum line. It is thought that the calculation result with ion spectrum is the maximum temperature in the channel, reflecting the thermodynamic state of the core current channel. The temperature calculated by the atomic spectrum is higher than the one by the continuous spectrum in the low-energy region. It is thought that in the outer channel there is a composite process of plasma, causing the plasma energy dissipation and lower temperature. The method of continuous spectrum calculating the temperature corresponding to different areas in the channel can more fully reflect the characteristics of the temperature distribution in the channel.

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