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Communication

Correlation between the Channel Discharge Current and Spectrum of a Single-Stroke Lightning Flash to Canton Tower

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Abstract: The intense current of lightning plasma can emit radiation across various parts of the electromagnetic spectrum. Spectral observation is an effective means to understand the radiation characteristics of lightning channels at different wavelengths. In this context, the spectra and channel current of a single-stroke lightning flash to Canton Tower were acquired from the Tall-Object Lightning Observatory in Guangzhou using a slitless high-speed spectrograph and a Rogowski coil. Spectral correction was applied for enhanced spectral analysis. The relationship between the intensities of different spectral lines and the directly measured current of the lightning channel was investigated for the first time. The results indicated that the duration of the ionic lines in the visible region can be up to one millisecond during the entire discharge process, which is clearly longer than the duration reported in previous research. There always exists a good exponential relationship ($y = ax^b$) between the intensities of ionic lines and the channel current with an exponent value (b) very close to 2 and with a coefficient of determination (R^2 value) higher than 0.99, whereas the exponential relationship between many atomic lines and the channel current has an exponent value clearly smaller than 2 with a relatively lower R^2 value, which implies that the intensities of ionic lines are evidently associated with the square of the current, while the intensities of atomic lines have relatively weak exponential correlation with the current. We also preliminarily verified this conclusion with temperature derived from the ionic and atomic lines. The results indicated that due to the time integral of the current squared, the cooling rate of the temperature derived from the ionic lines in the channel core is not significant when the current decreases, while the cooling rate of the temperature derived from the atomic lines of the surrounding corona sheath channel presents a pronounced decline with a decrease in current.

Keywords: lightning channel spectral characteristics; channel current; correlation; channel temperature; return stroke

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1. Introduction

The channel discharge current of lightning is considered one of the most critical lightning physics parameters. The enormous power generated by the lightning current rapidly heats the lightning channel, turning it into a plasma channel and emitting light radiation. However, due to the randomness of natural lightning discharges, it is difficult to measure the channel current directly. Conversely, optical measurements of the lightning channel are more feasible. Therefore, researchers have long been dedicated to exploring the relationship between lightning channel current and its luminosity, trying to indirectly obtain the channel current through optical observations. Flowers [1] first compared a discharge current lasting several milliseconds with channel luminosity in laboratory spark discharge experiments. He found that although an increase in discharge current would enhance the light intensity, there was not a direct proportional relationship between them. Moreover, Wang et al. [2] observed that the current and luminosity at the bottom of artificially triggered lightning channels had a linear relationship during their rising phase, but this relationship disappeared after reaching its peak. Zhou et al. [3] further discovered that during the slow decay phase of triggered lightning return strokes and M-components, there was a significant correlation between current and luminosity. However, during the initial rapid decay phase of the return stroke, this correlation was not evident.

These studies have made significant contributions to our understanding of the relationship between lightning current and luminosity. Nevertheless, it is essential to recognize that the process leading to the luminosity of a lightning channel is complex. The channel luminosity mentioned in previous studies typically refers to the integrated contribution of lightning radiation, which is a polychromatic signal superposed with all monochromatic signals in a specific spectral range of the camera sensor or photomultiplier. However, the spectral structure of radiated light changes during different phases of lightning discharge, and traditional optical observations cannot capture these details. Spectral observation is an effective means to understand the radiation characteristics of lightning channels at different wavelengths.

Regarding the research on the spectral characteristics and discharge properties of lightning, Qu et al. [4] found that the total spectral intensity is proportional to the amplitude of electric field change, and there is a positive correlation between temperature and the thermal effects characterized by current. In the spectral analysis on return strokes and their following continuing currents, Wang et al. [5] discovered that the amplitude of electric field change is linearly related to the total intensity of ionic lines. As the channel height increases, the variations in the total intensity of ionic lines are consistent with the current changes along the channel in the lightning models. Fan et al. [6] employed the transmission line model to calculate the current from the radiated electric field. A positive correlation between the current and the total intensity of ionic lines was found, and a semi-empirical method to obtain the current using the total intensity of ionic lines was proposed. However, constrained by the difficulty of direct channel current measurement, the electrical properties of lightning in these studies are understood through the electric field measurement. The electric field change only can reflect the amplitude of the current; it cannot reflect the current for the whole discharge process. Hence, using the directly measured channel current data to study its correlation with spectral characteristics is very necessary.

As previously noted, researchers can carry out the measurement of lightning current waveforms through triggered lightning [7–9]. Walker and Christian [10] discovered that variations in current within the lightning channel are synchronous with enhancements in its spectral characteristics, especially during the continuing currents of triggered lightning. Additionally, lightning current measurements can also be derived from tall-object lightning [11–13]. Chen et al. [14] reported the first direct measurement of lightning current on the Canton Tower. Their results indicated an approximate quadratic relationship between the maximum peak current and the initial peak luminosity for subsequent strokes within the same upward flash.

In the summer of 2021, a Rogowski coil was installed at the top of the Canton Tower to directly measure the lightning channel current. Additionally, a slitless high-speed spectrograph was set up for the acquisition of lightning spectral data. The aim of this paper is to present the correlation between the channel current and the intensities of ionic lines and atomic lines based on the above measurements.

The rest of this paper is organized as follows. In Section 2, the lightning observation experimental setup and the theory for lightning channel temperature calculations are described. Section 3 presents an overview of the lightning flash analyzed in this paper, corrections to the lightning spectra, and the preliminary results of the analysis of the correlation between spectral lines and currents and the time evolution of the lightning channel temperature. Section 4 presents a discussion on the impact of upper excitation energy of spectral lines on their intensity's dependency on current, proposing new insights into establishing a function between radiative intensity and current. In Section 5, this paper ends with preliminary conclusions.

2. Instrumentation and Methods

2.1. Instrumentation

Comprehensive observations of lightning striking tall structures in Zhujiang New Town have been conducted at the Tall-Object Lightning Observatory in Guangzhou (TOLOG) for a dozen years since 2009 [15]. The lightning flash analyzed in this study occurred at the top of the Canton Tower, the tallest building in Guangzhou with a height of 600 m. Spectral observations were set up at the main station of the TOLOG on a 100 m high building approximately 3.3 km away from the Canton Tower. The recording system of the spectrograph was a Photron FASTCAM Mini AX200 high-speed camera, manufactured by Photron Ltd., Tokyo, Japan. The camera was set at a sampling rate of 14,400 frames per second (fps) with an image resolution of 896 × 512 and a recording length of 1.73 s. The camera featured a CMOS sensor array with a dynamic range of 12 bits, a spectral response range of 400–1000 nm and a pixel size of 20 × 20 μm. The focal length of the lens was 20 mm. A plane transmission grating with a groove density of 600 lines/mm was put in front of the lens as the splitting system of the spectrograph. Spectral corrections for the spectrograph will be presented in Section 3.2. The atmospheric attenuation response was not included, primarily due to the lack of precise meteorological visibility data, which are essential for accurately determining the atmospheric transmission coefficient. One Rogowski coil, custom-manufactured by Power Electronic Measurement Ltd., Nottingham, United Kingdom, was installed at the Canton Tower to measure the lightning channel current. The coil was integrated with an analogue integrator and featured a frequency response ranging from 0.1 Hz to 3 MHz and a saturation level of 240 kA. The output from the analogue integrator was recorded using a 16-bit ADLINK PCIE-9834 express digitizer, manufactured by ADLINK Technology Inc., Taoyuan, Taiwan, featuring a sampling rate of 10 MS/s, a recording duration of 2 s, and a pre-trigger time of 1 s. The reliability of the current measurement system has been verified in Chen et al. [14].

2.2. Theory and Assumptions

To estimate the temperature of lightning plasma from its emission spectrum, the following assumptions are required [16–18]: (a) the lightning channel is optically thin, and (b) the channel satisfies the conditions for local thermodynamic equilibrium (LTE). Uman [17,19,20] has verified the validity of these assumptions. Then, the channel temperature can be obtained using the Boltzmann plot method through the following equation [21]:

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

where c is a constant, I is the intensity of the spectral line, λ is the wavelength, g is the statistical weight, A is the transition probability, and E is the excitation energy. Several spectral lines from the same element and same ionization state but different energy level transitions are selected to calculate the temperature. Taking the left term of Equation (1) as the ordinate, and the excitation energy as the abscissa, the least square method is used to fit a line, and the temperature T can be derived from the slope of the line.

3. Results

3.1. Overview

The downward negative cloud-to-ground lightning flash analyzed in this study occurred at 13:57:10 UTC on 22 June 2021. This flash is labeled FA21029 in the TOLOG database. Figure 1 presents consecutive spectrum frames captured by the high-speed spectrograph preceding and during the return stroke of flash FA21029. Time 0 is set at the onset of the return stroke, and the timestamp of each spectrum frame is set at the beginning time of its exposure duration. The position of the top of Canton Tower is marked in Figure 1a, at a height of 600 m above ground level (AGL). The junction point of the lightning channel of flash FA21029 marked in Figure 1a reveals that the downward negative leader tip connected to the lateral surface of the upward connecting positive leader, similar to the case presented in Lu et al. [15].

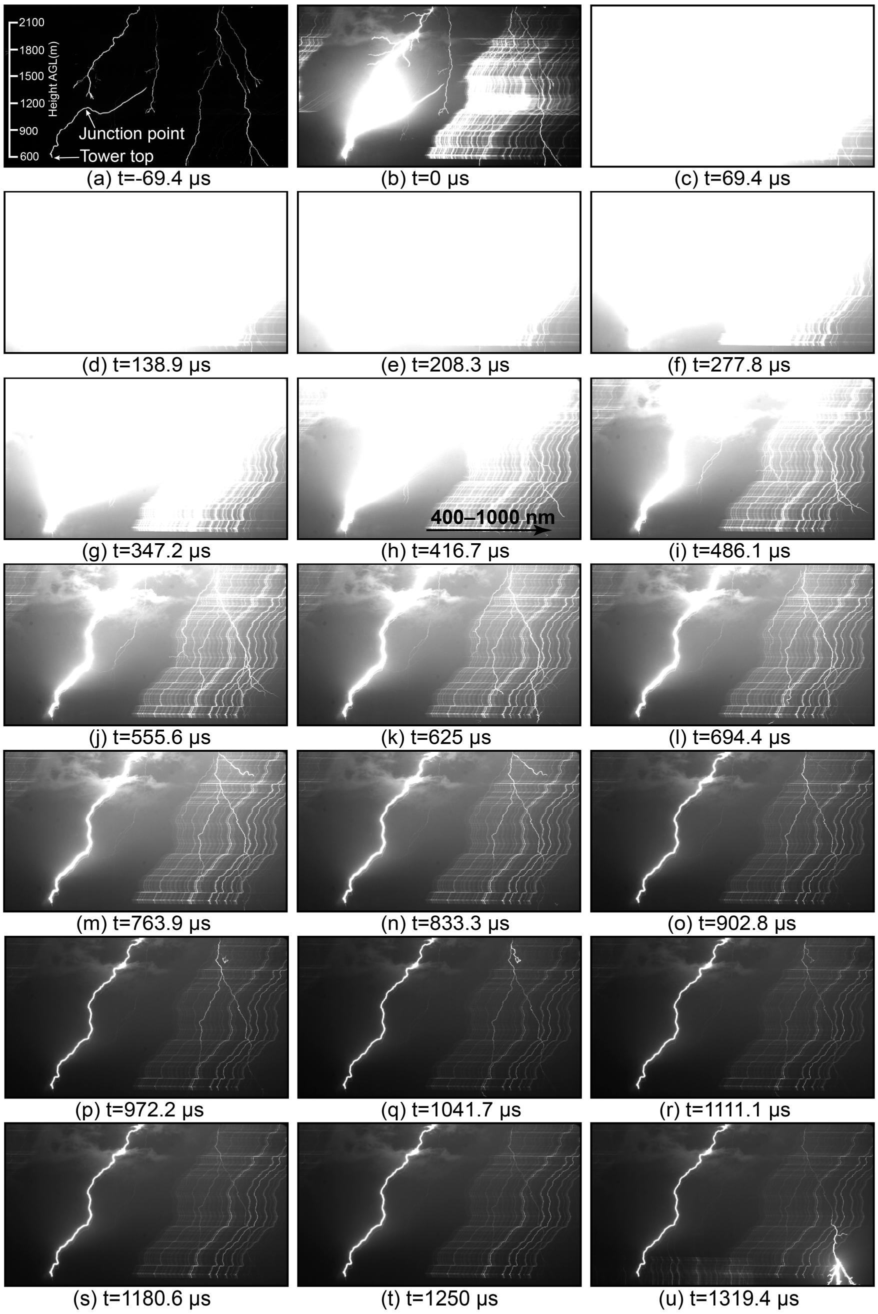

Figure 1. Consecutive spectrum frames preceding and during the return stroke of flash FA21029.

Figure 2a,b, respectively, show the luminosity and current variations of flash FA21029. The duration of the discharge is approximately 4 ms, while a clearly identifiable spectrum lasts for about 1.3 ms. The overall channel luminosity and current in Figure 2 suggest that a short continuing current (CC) process occurs following the return stroke. To compare the current data and the intensities of spectral lines at an identical temporal resolution, subsection-averaging resampling was applied to the current data, as shown in Figure 2b.

The effect of random noise was decreased using this procedure and the current characteristics of slow changes in the return stroke decay process are presented.

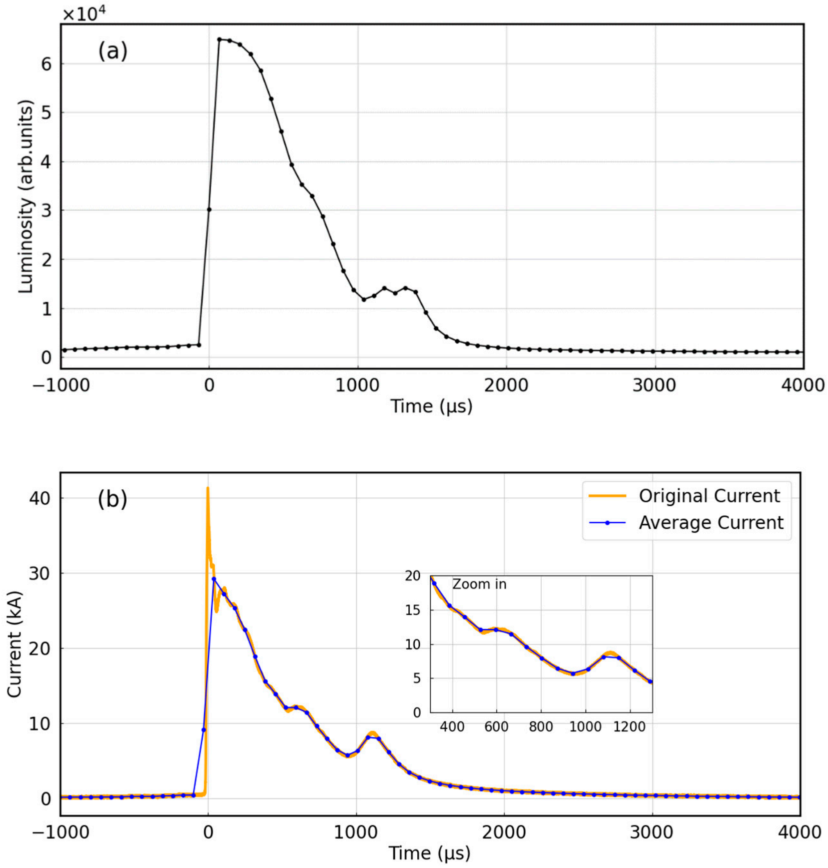

Figure 2. Time evolution of (**a**) the total channel luminosity and (**b**) simultaneous measured current of flash FA21029.

3.2. Spectral Analysis before and after Correction

Considering that the transmission grating and high-speed camera exhibit different sensitivities to light at different wavelengths, leading to distortions in the observed spectral intensities, it is imperative to correct for distortions based on the spectral response characteristics provided by the manufacturers of the grating and camera. The response curves are shown in Figure 3, where the synthesized response is represented by the green curve, with the peak sensitivity around 650 nm. It can be indicated that the spectrum structure is significantly affected by the spectrograph's efficiency.

Figure 4a,b illustrate the time evolution of the spectra before and after correction, respectively. Due to the oversaturation of spectral lines preceding the sixth frame (t = 347.2 μs) of the return stroke, only discernible spectra from the seventh frame (t = 416.7 μs) onward are presented and analyzed. Significant changes in spectral structure can be observed between the corrected and original spectra data. For the original spectra data before correction, intensities of ionic lines are comparable to those of atomic lines, and both exhibit relatively slow decay as the current decreases. Moreover, the overall spectral structure shows minor variations over time. However, for the corrected spectra data in Figure 4b, a distinct temporal evolution in the overall spectral structure is evident. At earlier stages during the decay process of the discharge, the emission is dominated by ionic spectral lines in the visible wavelength region. Subsequently, as the current diminishes, the intensities of ionic lines decline sharply, while the intensities of atomic lines demonstrate a more gradual decay. Consequently, the rapid attenuation of the intensities of ionic lines leads to a shift in the primary spectral contribution toward the near-infrared region.

However, in the late stage of the discharge, the ionic lines NII 404.3 nm, NII 444.7 nm, NII 463.0 nm, and NII 480.3 nm are still clearly distinguishable. In the spectra of triggered lightning return strokes, Walker and Christian [22] observed that the intensities of singly ionized lines diminish below the threshold in less than 30 μs. In the corrected spectra of Figure 4b, it can be seen that the singly ionized lines are clearly identifiable even at t = 1250 μs. This duration of the singly ionized lines is clearly greater than in previous research, which has reported that the duration of the singly ionized lines is in the tens of microseconds.

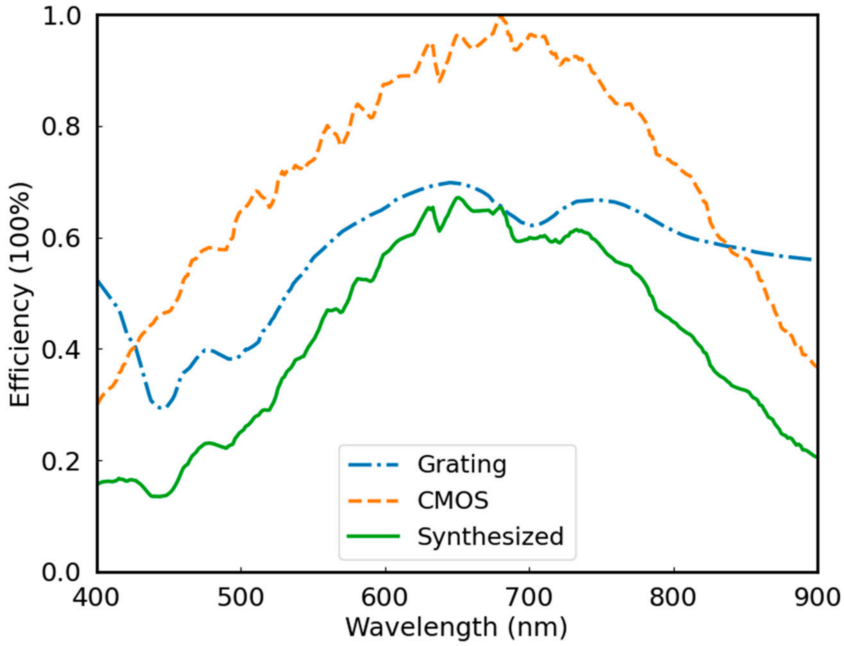

Figure 3. Spectrograph response curve.

3.3. Correlation between Current and Spectral Lines Intensities

Combined with directly measured current data, Figure 5 further elucidates the spectral characteristics by detailing the temporal variations in the intensity of specific spectral lines. It can be seen in Figure 5b that except for the neutral OI 777.4 nm, all spectral lines intensities diminish concurrently with the decline in current. Specifically, ionic lines such as NII 404.3 nm, NII 417.6 nm, NII 444.7 nm, and NII 480.3 nm in the short-wavelength region exhibit a more rapid rate of attenuation. Conversely, most atomic lines demonstrate a slower decreasing trend, with the intensity of the OI 777.4 nm line even showing a slight increment. At t = 833.3 μs, the OI 777.4 nm line emerges as the strongest spectral line and continues to maintain relatively high intensity thereafter. Finally, it also follows the general trend of current. This study offers nuanced insights into the distinct dynamic behavior of different spectral lines in relation to current variations throughout the decay stage of the return stroke of flash FA21029.

The research by Zhao [23] observed near-infrared range emissions in lightning channels and found that the OI 777.4 nm spectral line could be detected throughout the entire luminous phase from the leader to the return stroke. Moreover, the intensity of OI 777.4 nm was found to be correlated with the amplitude of the electric field change. Similarly, Zhang [24] compared the spectra in the near-infrared and visible ranges during the lightning return stroke. The results indicated that while visible spectra were primarily associated with the initial and developmental stages of the lightning return stroke, the near-infrared spectra were mainly observed in the later stages of lightning development. This study also highlighted that, during the recombination processes within the plasma of the lightning discharge channel, the adsorption of oxygen atoms onto other particles and their subsequent desorption significantly contribute to the increased number of oxygen atomic spectral lines observed in the near-infrared spectrum. These interactions primarily occur between oxygen atoms and the high-energy particles present in plasma, influencing the radiative properties of lightning. The two processes of adsorption and desorption of oxygen during the recombination process are likely reasons for the relative intensity of OI 777.4 nm being higher than usual.

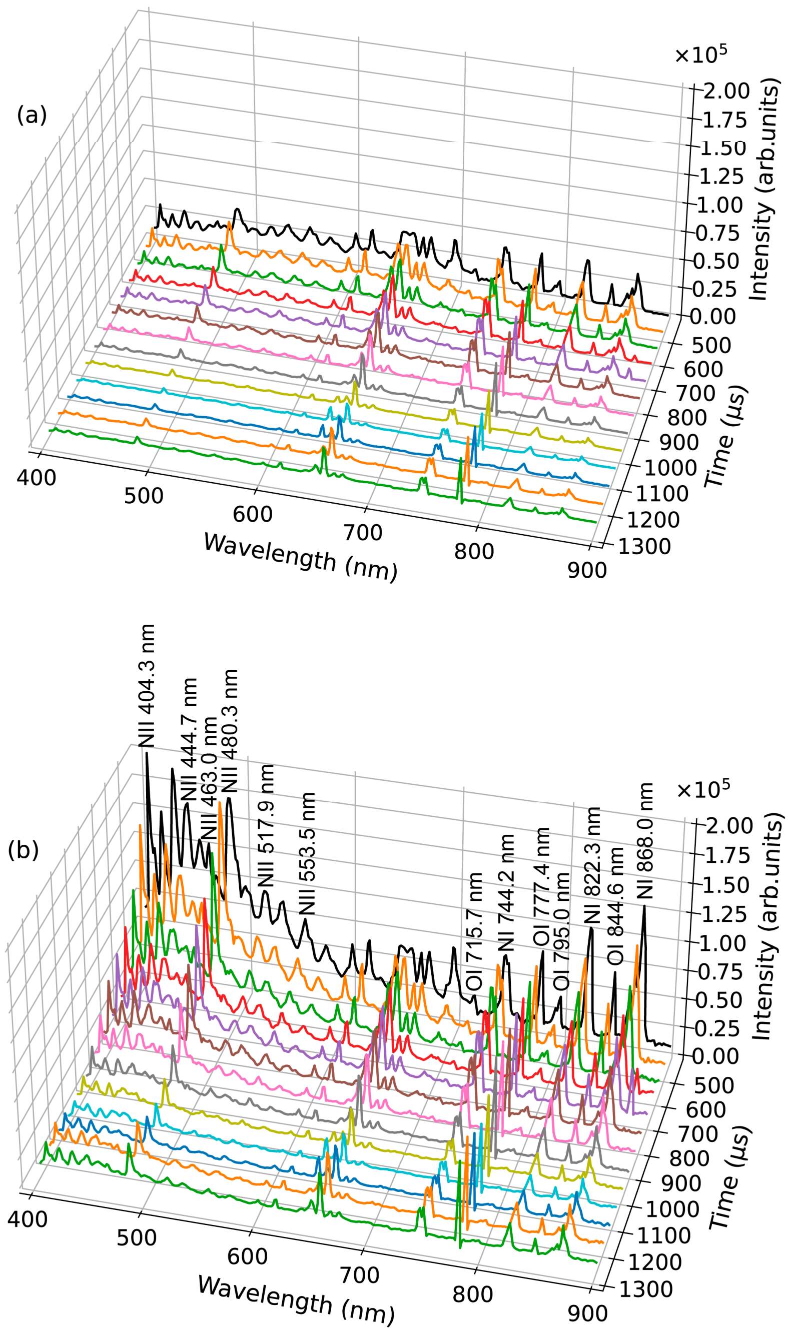

Figure 4. The evolution of spectrum (**a**) before and (**b**) after correction.

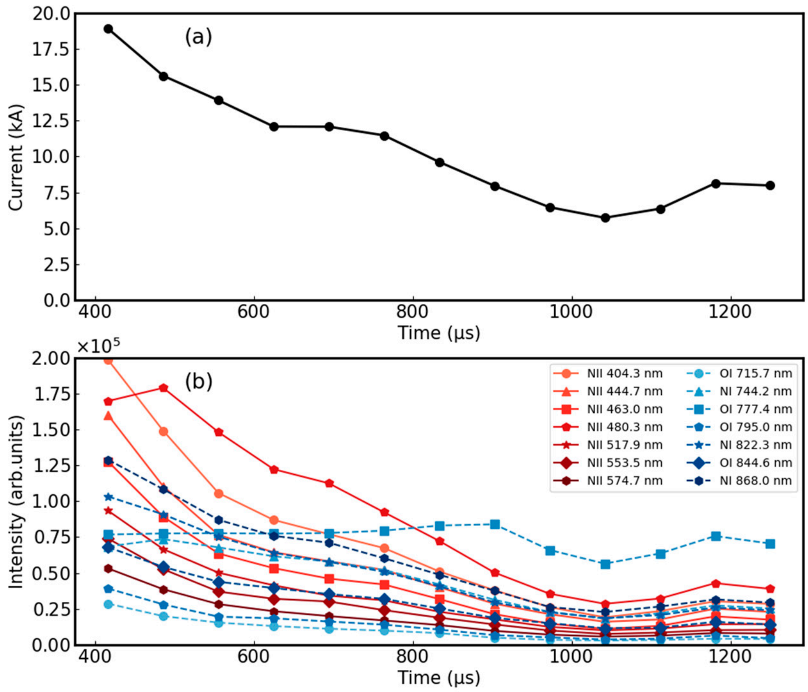

Figure 5. Variation in (**a**) current and (**b**) spectral lines intensities for decay stage of the lightning discharge.

In Figure 6a,b, scatter plots of current versus the intensities of various ionic and atomic spectral lines are presented, respectively. Power law fits in the form of $y = ax^{b}$ are performed, with the results displayed in the figure legends. The coefficients of determination (R^2) relating to the intensities of ionic lines and current are all higher than 0.99. Furthermore, the exponent values for these lines are notably close to 2, indicating that the intensity of the ionic lines is almost directly proportional to the square of the current. However, for the fits of intensities of atomic lines and current, the coefficients of determination are slightly weaker than those for the fits of intensities of ionic lines and current, with R^2 values ranging from 0.87 to 0.99. The exponent values for these lines range from 1.08 to 2.03. It is noteworthy that the intensities of OI 715.7 nm and OI 795.0 nm exhibit a high coefficient of determination relating to current, both at 0.99. The exponents are both 2.03, close to 2. This seems to be consistent with the previously mentioned relationship between the intensities of ionic lines and current.

According to previous studies [25,26], the lightning channel consists of a current-carrying core surrounded by an external corona sheath. Uman and Orville [27] demonstrated that the emission lines with higher excitation energy, such as NII and OII, are mainly from the current-carrying core. The study by Orville [28] reported that emission lines including NII, OII, NI, and OI come from a region with diameters larger than those that contain only NI and OI emission lines. Therefore, it can be inferred that the neutral lines with lower excitation energy primarily come from the surrounding corona sheath. This theory aligns with further analyses of the spectral characteristics of lightning in relation to electric fields as detailed by Wang et al. [5]. The results of this study show that the intensities of ionic lines are almost directly proportional to the square of the current, with exceptionally good coefficients of determination (R^2). However, for the intensities of atomic lines, while there is a discernible correlation, the coefficients of determination (R^2) relating to current are relatively poorer. Consequently, these results affirm that the radiation from ionic lines mainly originates from the current-carrying core of the lightning channel.

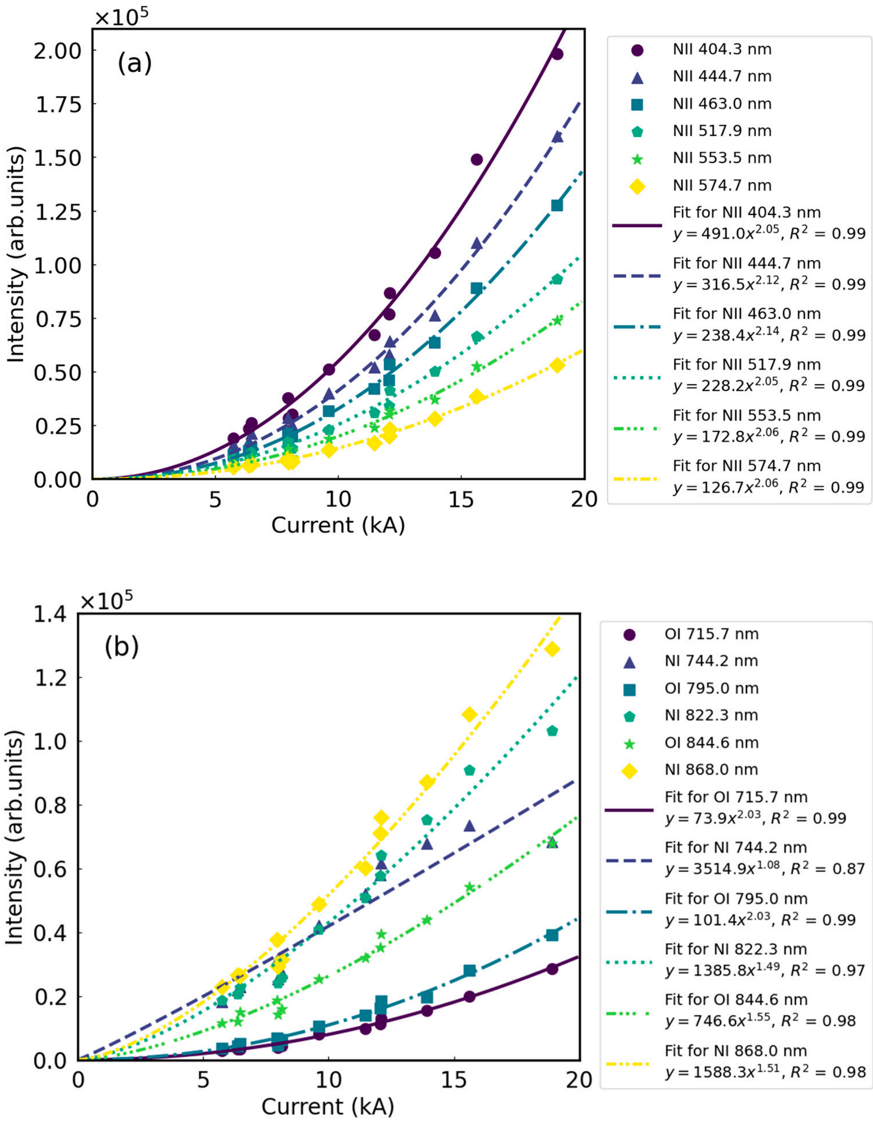

Figure 6. Power law fits of intensities of (**a**) ionic lines and (**b**) atomic lines versus current.

3.4. Channel Temperature

Using Equation (1), channel temperatures were calculated from selected ionic lines (NII 480.3 nm, NII 553.5 nm and NII 574.7 nm) and the atomic lines (OI 715.7 nm, OI 777.4 nm and OI 844.6 nm), denoted as T_{NII} and T_{OI}, respectively. Figure 7a shows their temporal evolution in comparison with the changes of current and Figure 7b shows the relationship between the time derivative of the temperature and the current square. It can be observed from Figure 7a that as the current decreases, the temperature derived from the NII lines exhibits a slight decline with an overall minimal variation. However, the temperature calculated from the OI lines demonstrates a more significant downward trend.

During the discharge process, due to the thermal effect of the current, the channel temperature is related to the time integral of the square of the current. The temperature calculated from the neutral atomic lines changes in the same way as the observed current, which subtly indicates that the main contribution to the temperature derived from the neutral atomic lines is not from the observed current directly. On the contrary, the temperature variation over time calculated from the singly ionized ionic lines suggests that the current mainly contributes to the temperature calculated from the ionic lines. From Figure 7b, the time derivative of temperature derived from the singly ionized ionic lines has a little change when the current square decreases, while that derived from the neutral atomic lines is evidently reduced with a decrease in the current squared. This just indicates that due to the time accumulation of the current squared, the change in temperature derived from the singly ionized ionic lines in the channel core is not significant. This also indicates that the current observed at the bottom of the lightning channel is mainly composed of the longitudinal current from the channel core, with a smaller proportion from the radial corona current. Additionally, the conductive cooling from the exterior should be non-negligible. Hence, the temperature calculated from the OI lines of the surrounding corona sheath channel demonstrates a pronounced decline with time, as shown in Figure 7a. Also, the cooling rate derived from the neutral atomic lines in the surrounding corona sheath channel presents a pronounced decline with a reduction in the current squared, as shown in Figure 7b.

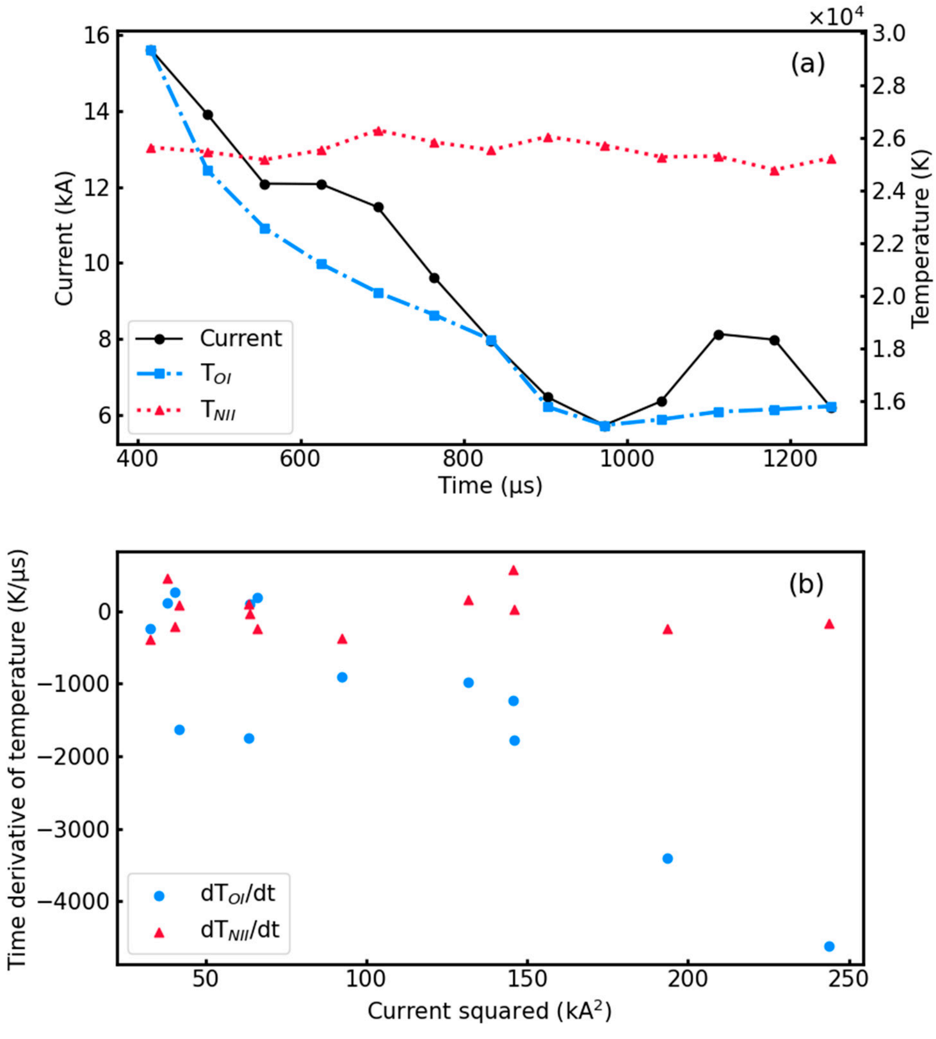

Figure 7. (**a**) The evolution of channel temperature and current with time. (**b**) Time derivative of temperature versus current squared.

These results also corroborate the validity of the models pertaining to the lightning channel structure and affirm the fact that ionic line radiation mainly emanates from the channel core, whereas atomic line radiation chiefly originates from the corona sheath.

4. Discussion

Orville [29] observed that the transition spectral lines of singly ionized ions primarily appear in the emission spectrum of the return stroke channel. The strong transition spectral lines of NII with high excitation energy can provide significant insights into the discharge characteristics. Building upon the dynamics of the lightning channel corona sheath [26,30], the channel core is the initial pathway formed by discharge ionization. Subsequently, radial energy transmission occurs, leading to the formation of the surrounding corona sheath. Hence, there must be an inherent correlation between various emission spectral lines and the current. Carvalho et al. [31] elucidated that the proportionality of luminosity to the square of the current is physically reasonable, implying it is consistent with the input power of the current, assuming a constant resistance per unit length. The results shown in Figure 6 are consistent with Carvalho et al. [31]. The radiative intensity of ionic lines exhibits a power-law fit with the current, where the exponent is close to 2, and the fit determination coefficient is commendable.

It should be noted that as mentioned in Section 2, the spectral correction in this work does not consider the effect of atmospheric attenuation. For a single spectral line, the deviation in the spectral response value only affects the value of the coefficient (a) in the power exponential fit ($y = ax^b$) of the intensity of the line to the current and has no effect on the exponential term (b), as well as the R^2 value. This paper focused on the exponential term and the R2 value in the analysis of the correlation between intensities of spectral lines and current. Thus, the neglect of atmospheric attenuation in the spectral correction should not affect the conclusions of this paper.

For the atomic lines OI 715.7 nm and OI 795.0 nm presented in Figure 6, their upper excitation energies are 14.46 eV and 14.10 eV, respectively, which are notably higher than those of other atomic lines with upper excitation energies of 12.00 eV, 11.84 eV, 10.99 eV, and 11.76 eV, respectively, for NI 744.2 nm, NI 822.3 nm, OI 844.6 nm, and NI 868.0 nm. The fits of the intensities of these two atomic lines with the current demonstrate results similar to the fit relating the intensities of ionic lines with high excitation energies and the current. This is reasonable. Since the specific locations of different radiative spectral lines on the cross-section of lightning channel cannot be established at present, we can only infer that the ionic lines with high excitation energies mainly come from the current-carrying core, while neutral lines with lower excitation energies primarily originate from the surrounding corona sheath. At the transition between the high-temperature channel core and the cooler surrounding corona, there are also spectral lines like OI 715.7 nm and OI 795.0 nm, which have excitation energies lower than singly ionized ionic lines but higher than other neutral atomic lines. At this point, these neutral atomic lines with higher excitation energies are also mainly related to the current in the channel core. This suggests that the dependency of spectral line intensity on the current is significantly related to the upper excitation energy of the spectral line.

Figure 6 reveals different correlations between intensities of different spectral lines and the current. Since the luminosity of the lightning channel is a composite of these spectral lines, the overall luminosity of the channel and the current are positively correlated, albeit in a nonlinear and intricate manner. This complexity has made it challenging in past research to succinctly summarize the relationship between lightning channel luminosity and current. However, an insight derived from this study suggests that monochromatic light, especially ionic lines in visible wavelength range, could be more suitable than the overall luminosity of the lightning channel to establish a function between radiative intensity and current. Noting that these conclusions are based on preliminary data and analysis of the single-stroke lightning flash, more extensive research is still required to validate these observations and to further understand the mechanisms.

Additionally, Figure 7a indicates the temperature derived from the neutral OI lines decays faster with time than the current, and it does not reflect the sudden increases in the current at t = 625 us and t = 1111.1 us. So, there must be some other cooling mechanisms at work besides the cooling from the corona sheath mentioned above. A study of this aspect will be conducted in the future.

5. Summary

The direct current measurement and spectral observation of a lightning flash that occurred at the top of the Canton Tower were performed simultaneously. The corrected spectra showed that the duration of the ionic lines in the visible region can be up to one millisecond, which is significantly longer than previously reported. The intensities of ionic lines in the visible wavelength range are significantly greater than those of the atomic lines in the infrared region at earlier stages during the decay process of the lightning discharge.

The correlation between the directly measured current and the intensities of ionic lines and atomic lines in the spectra has been analyzed for the first time. Our preliminary findings indicate that, as the current diminishes in the early decay stage, the intensities of ionic lines decline sharply, while the intensities of atomic lines demonstrate a more gradual decay. The primary part of the emission spectrum gradually shifts from the visible range to the near-infrared region. The intensities of ionic lines are almost directly proportional to the square of the current, with exceptionally good coefficients of determination (R^2), while the exponent values for the power law fit between the intensities of atomic lines and current are smaller, with relatively poorer coefficients of determination (R^2). These initial results suggest that, compared to the overall luminosity of the lightning channel, the intensity of a specific single ionic line within the visible wavelength range could be more suitable for establishing a function between radiative intensity and current.

The upper excitation energies of OI 715.7 nm and OI 795.0 nm are notably higher than those of other atomic lines. The fits of the intensities of these two atomic lines with the current demonstrate results similar to the fit relating the intensities of ionic lines with high excitation energies to the current. This suggests that the dependency of line intensity on the current is significantly related to the upper excitation energy of the spectral line.

The temperature derived from the NII ionic line exhibits a slight decline with minimal variation overall, while the temperature calculated from the OI atomic lines demonstrates a more significant downward trend. These results affirm the lightning channel model with a hot current-carrying core emitting ionic lines and a cold corona sheath emitting neutral atomic lines.

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