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Characteristic parameters of positive cloud-to-ground lightning channel

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The high time-resolved spectra of two natural positive cloud-to-ground (CG) lightning of which one of them contains multiple return strokes have been taken by a high-speed slit-less spectrograph. On combining with the synchronous electric field change waveform, the temperature, electrical conductivity of the return stroke channel, radius of the core current channel and the peak value of current are calculated. The correlation between the peak current and the time interval of five M components which overlapped with the continuous current following the subsequent return stroke R1 of multiple return strokes positive CG lightning were analysed. The results show that the average temperatures of the return stroke channels for two positive CG lightning are about 28,900–29,800 K, the radius of the core current channel is about 0.36–1.01 cm, the estimated peak currents of the return strokes are about 18.6–38.0 kA, which are all larger than the typical values of common negative CG lightning. The peak currents of the M components are positively correlated with the time intervals between them.

Keywords. Temperature; discharge current; M component; positive CG lightning; radius of the core current channel; conductivity.

1. Introduction

The large current and strong electromagnetic radiations caused by the lightning discharge are the main causes of forest fire, power transmission system damage and many other lightning disasters (Soriano *et al.* 2005). Positive cloud-to-ground (CG) lightning usually has a strong return stroke current, and is mostly followed by continuous current, which is more harmful. The powerful return stroke current heats the discharge channel to tens of thousands of degrees and forms a plasma channel. The temperature and electrical conductivity are basic parameters reflecting the physical characteristics of a lightning discharge channel (Lu *et al.* 1994; Li *et al.* 2012; Agnes *et al.* 2013). At present, there are few reports on the temperature and other characteristic parameters of positive CG lightning channel.

Optical and electrical observations show that most positive CG lightning usually contains only one return stroke. The probability of positive CG lightning with multiple return strokes is very low. From National Lightning Detection Network data, Lyons (1996) found that among 2 million positive CG lightning, only 0.04% of them contain the multiple return strokes, whereas about 80% of negative flashes contain two or more strokes (Rakov and Huffines 2003). Saba *et al.* (2010) analysed the data recorded using a high-speed camera and lightning location system, and found that 81% of 103 positive flashes have one return stroke and the 21 of them have multiple return strokes. Nag and Rakov (2012) reported that the peak current range is 20–234 kA with a mean of 75 kA for 48 positive lightning according to the National Lightning Detection Network data. In general, 75% positive flashes have at least one long continuous current, and its duration time is about 40 ms, only 30% negative flashes have continuous current (Saba *et al.* 2010). The temperature and electrical conductivity of the discharge channel are closely related to the spectral properties in the lightning process (Qu *et al.* 2011). In this paper, based on the time-resolved spectra of two positive CG lightning return stroke processes recorded by a slit-less high-speed spectrograph, and according to the transport theory of air plasma, the temperature and the electrical conductivity of lightning discharge channel are calculated. Combining with the synchronised electric field change data, the peak current, the radius of core current channel and the other parameters which are related to the discharge properties are obtained. Reference data are provided for further exploration of the current transfer characteristics and thermal effect of the positive CG lightning process.

2. Theoretical methods

2.1 *Channel temperatures*

Based on the spectral information to calculate the temperature of the lightning discharge plasma channel, two basic assumptions must be met:

(1) The lightning channel is optically thin for the concerned spectral line.
(2) Within the period of research time, the channel is in the local thermodynamic equilibrium (LTE).

Uman and Orville (1965); Uman (1969) have confirmed that the lightning plasma channel satisfies these two basic assumptions. Under the condition of LTE, the relationship between the transition parameters of the spectral line and the channel temperature is as follows:

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

where λ is the wavelength, T is the temperature, c is a constant, I is the relative intensity of the spectral lines, E is the upper excitation energy, k is a Boltzmann constant, A is the transition probability and g is the statistical weight. The value of gA can be obtained from the NIST database. On fitting the straight line with $\ln(I\lambda/gA)$ as the vertical coordinate and E as the abscissa, the temperature can be calculated through the slope parameter $(-1/kT)$.

2.2 *Conductivity of the lightning discharge channel*

The conductivity of the lightning discharge channel was (Capitelli *et al.* 2000; Chang *et al.* 2010; Wang *et al.* 2016b)

$$\sigma = 3n_{\mathrm{e}}^2 e^2 \sqrt{\frac{\pi}{2m_{\mathrm{e}}kT}} \begin{vmatrix} q^{11} & q^{12} \\ q^{21} & q^{22} \end{vmatrix} \left| \begin{vmatrix} q^{00} & q^{01} & q^{02} \\ q^{10} & q^{11} & q^{12} \\ q^{20} & q^{21} & q^{22} \end{vmatrix}^{-1} \right|, \tag{2}$$

where n_{e} is the electron density and the q^{mp} (Devoto 1967) elements are co-determined by the channel electron density, the particle number density and the collision integral.

A study of the components of lightning discharge plasma shows that the concentration of ions which are more than three times the ionisation is relatively low, so the contributions of these ions to the channel characteristic parameters will be much smaller. The components in the channel mainly include: NI, NII, NIII, OI, OII, OIII, ArI, ArII, ArIII and electron. Therefore, the calculation of conductivity mainly involves the collisions between electron and electron as well as electron and the first or second ionised ions.

The collision integral between the i and j particles is followed as

$$Q_{ij}^{(\mathrm{l,s})}(T) = \frac{4(l+1)}{(s+1)!\left[2l+1-(-1)^{\mathrm{l}}\right]} \int_0^\infty \mathrm{e}^{-r^2}\gamma^{2s+3}Q_{ij}^{(1)}(\xi)\,\mathrm{d}\gamma, \tag{3}$$

where $Q_{ij}^{(1)}(\xi)$ is the differential transmission cross section (Liboff 1959). The reduced relative speed is defined by $\gamma = \sqrt{(u_{ij}/2\kappa T)}\xi$ in which ξ is the relative speed of particles and u_{ij} is the reduced mass of the colliding particles.

2.3 *Radius of the core current channel*

Borovsky *et al.* (1995) has reported an electrodynamics model of lightning dart leaders and return strokes. In the model, both the dart leader and the return stroke are described as electromagnetic waves that propagate along a conducting lightning channel, and the electrostatic energy is stored in the leader channel. After a strong return stroke current causes the expansion and rapid heating, molecular dissociation and atomic ionisation of the channels, the stored energy is released. There are three main parts of the energy before the radial expansion of the channel (Borovsky *et al.* 1998):

$$\varepsilon = \varepsilon_{\text{thermal}} + \varepsilon_{\text{ionis}} + \varepsilon_{\text{disso}}, \tag{4}$$

$\varepsilon_{\text{thermal}}$ is the internal energy before the channel expanded, $\varepsilon_{\text{ionis}}$ is the atomic ionisation energy and $\varepsilon_{\text{disso}}$ is the molecular dissociation energy:

$$\varepsilon_{\text{disso}} = \pi r_{\text{init}}^2 L n_{\text{molec}} \tau_{\text{disso}}, \tag{5}$$

$$\varepsilon_{\text{thermal}} = \pi r_{\text{init}}^2 L\,(1+f)\,\frac{3}{2} n_{\text{atomic}} \kappa T, \tag{6}$$

$$\varepsilon_{\text{ionis}} = \pi r_{\text{init}}^2 L n_{\text{atomic}} f \tau_{\text{ionis}}, \tag{7}$$

for formulas (4)–(7), where r is the channel radius, L is the total channel length, T_{init} is the temperature before channel expansion, $f = 0.97$ (Wang *et al.* 2010) is the ionisation degree, $\kappa = 1.38 \times 10^{16}$erg/K is Boltzmann constant, $\tau_{\text{dissio}} = 9.8$eV is the dissociation energy of N_2, $\tau_{\text{ionis}} = 14.5$eV is the first ionisation energy for NI, n_{molec} and n_{atomic} are the number density of the molecular dissociation and atomic ionisation before channel expansion, respectively, and the $n_{\text{molec}} = 0.5 n_{\text{atomic}}$ (Borovsky *et al.* 1998).

Through the law of energy conservation, the energy (Borovsky *et al.* 1998) stored per unit length of the lightning channel is calculated by

$$\frac{\varepsilon}{L} = \lambda_{\text{q}}^2 \left[\frac{1}{2} + \lg\left(\frac{E_{\text{break}}}{E_{\text{cloud}}}\right)\right]. \tag{8}$$

Using equations (4)–(7) in equation (8), we get

$$r = \lambda_{\text{q}} \left[\frac{1}{2} + \lg\left(\frac{E_{\text{break}}}{E_{\text{cloud}}}\right)\right]^{1/2} (\pi n_{\text{atomic}})^{-1/2} \times \left[(1+f)\,\frac{3}{2}\kappa T + \frac{1}{2}\tau_{\text{disso}} + f\tau_{\text{ioniz}}\right]^{-1/2}, \tag{9}$$

where λ_{q} is the channel internal charge density, $E_{\text{break}} = 2.0 \times 10^6$V/m is the breakdown electric field value of air, the obtained value of the thunder cloud background electric field is $E_{\text{cloud}} = 5.0 \times 10^4$V/m (Borovsky *et al.* 1998).

According to the initial peak value of the electric field change waveform caused by the return stroke and based on the transmission line mode, the peak currents of the return stroke can be estimated.

2.4 *Estimation of the return stroke current*

Using the synchronous observation data of electric field change on the ground and corresponding theoretical models, the currents can be roughly estimated. The total electric field is given by

$$E_{\text{z}} = \frac{1}{4\pi\varepsilon_0} \int_{-h}^{h} \frac{2\,(z-z')^2 - r^2}{R^5} \int_{-\infty}^{t} i\,(z', t - R/c)\mathrm{d}t + \frac{2\,(z-z')^2 - r^2}{cR^4} i\,(z', t-R/c) - \frac{r^2}{c^2 R^3} \frac{\partial i\,(z', t-R/c)}{\partial t}]\mathrm{d}z', \tag{10}$$

where the first three terms represent the electrostatic field, the induction electric field and the radiation electric field, respectively. When the observed distance is longer than the length of the channel, the radiation field dominates the lightning electric field, and equation (10) is written as

$$E_{\text{z}} \approx \frac{1}{2\pi\varepsilon_0 c^2 r} \int_0^h \frac{\partial i\,(z', t-R/c)}{\partial t} \mathrm{d}z'. \tag{11}$$

If the observation site is far distant from the lightning discharge channel, we have

$$E_{\text{z}} = -\frac{\nu}{2\pi\varepsilon_0 c^2 r} i\,(0, t - r/c)\,. \tag{12}$$

Neglect the direction of the current and only consider the magnitude of the peak value, and we can rewrite (12) as

$$i_{\max} = \frac{2\pi\varepsilon_0 c^2 s}{v} E_{\max}, \tag{13}$$

where ε_0 is the vacuum dielectric constant, c is the speed of light, s is the horizontal distance between the lightning channel and observation site, v is the transmit speed of return stroke current, taking $v = 1.5 \times 10^8$ m/s (Wang *et al.* 2016a, b).

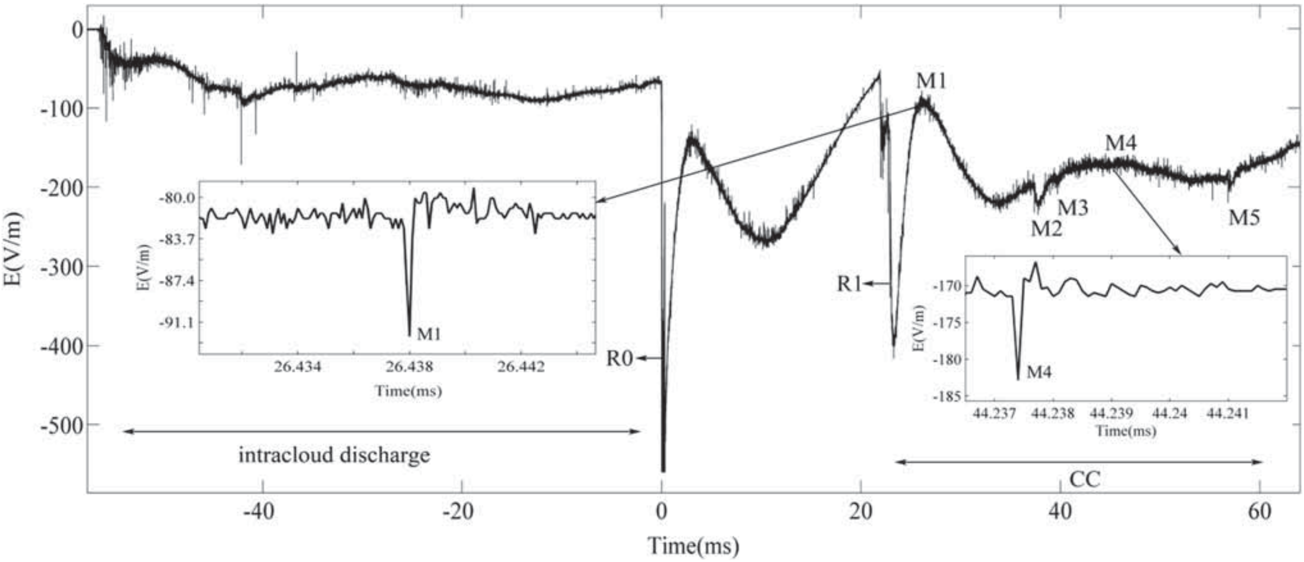

Figure 1. Electric field change caused by lightning A.

3. Instrumentation and discussion

3.1 *Instrumentation*

The spectra data of two CG positive lightning discharge processes were recorded by a slit-less spectrograph with a high-speed camera as the recording system, a plane transmission grating with 600 lines per millimetre was placed in front of the objective lens of the camera (Cen *et al.* 2014; Wang *et al.* 2014). The high-speed camera was set at 8000 fps with an image resolution of 1024 $\times$ 432. The synchronous electric field change data were obtained by the fast antenna system and slow antenna. Its time constants are 2 ms and 5.6 s with a frequency bandwidth of 100 Hz–3.2 MHz and 0.18 Hz–3.2 MHz, respectively. The fast and the slow antenna system synchronises with the high-speed camera system through GPS.

3.2 *Results and discussion*

The positive CG lightnings happened at the later stage of the thunderstorm process which lasted for about an hour and their occurrence times are 15:46:40 and 15:44:28, respectively. For convenience, they are named as A and B, respectively. Among them, lightning A is a relatively rare positive CG lightning with two return stroke processes, which are named as R0 and R1, respectively, where R0 is the first return stroke and R1 represents the corresponding subsequent return stroke. Lightning B is a single return stroke positive CG discharge process. According to the arriving time differences between light and sound produced by lightning, the distances from the observation site to the two lightning discharge channels are estimated to be about 12.5 and 13.9 km, respectively, and the altitude of the observation site is about 2560 m.

3.2.1 *Formation process of the positive CG lightning*

Figure 1 shows the electric field change caused by lightning A. The occurrence time of the first return stroke is set as 0 ms. It can be seen from figure 1 that there is an intracloud discharge process before R0, and a continuous current process that lasted for about 35 ms after R1. Brook *et al.* (1982) found that there is usually a continuous current process after the return stroke for the positive flash. Figure 1 also shows that the time interval between the two return strokes is about 22.9 ms. Saba *et al.* (2010) reported that the geometric average value of the time interval between the return strokes for positive CG lightning is 94 ms.

Figures 2 and 3 show the luminous channel and the corresponding electric field change of intracloud discharge before the subsequent return stroke R1 for lightning A, respectively. The intracloud discharges lasted for about 0.865 ms. As shown in figure 2(b and c), the channel initiated between the clouds, and it began going downward at about 22.678 ms (figure 2h). As shown in figure 3, the electric field changes appear as an obvious unipolar

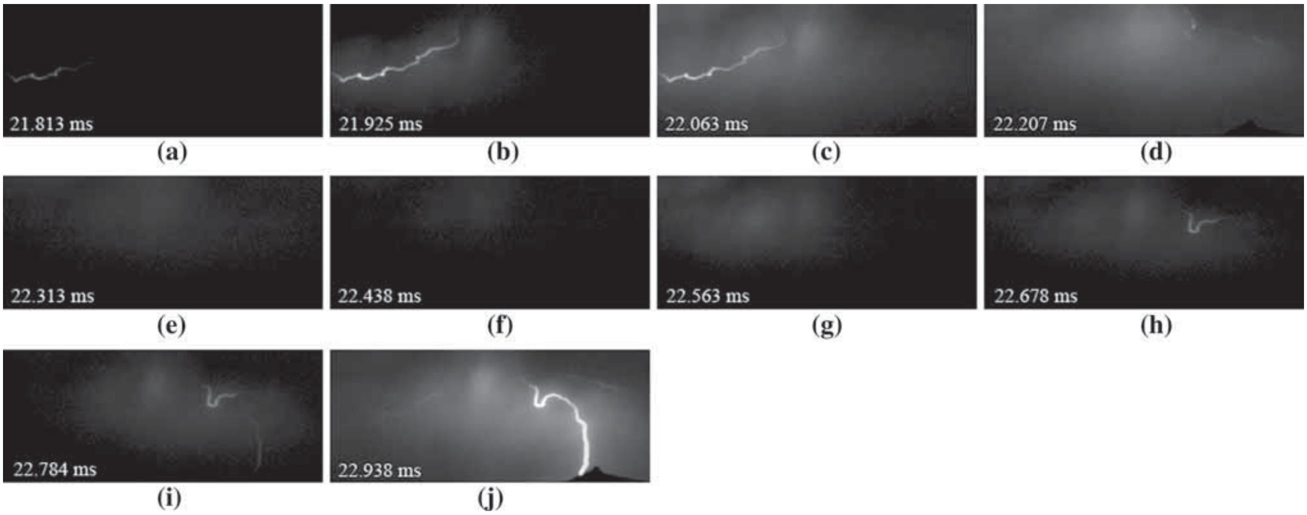

Figure 2. Luminous channel of intracloud discharge before the subsequent return stroke R1 of lightning A. (**a**)-(**j**) is arranged in chronological order of lightning development.

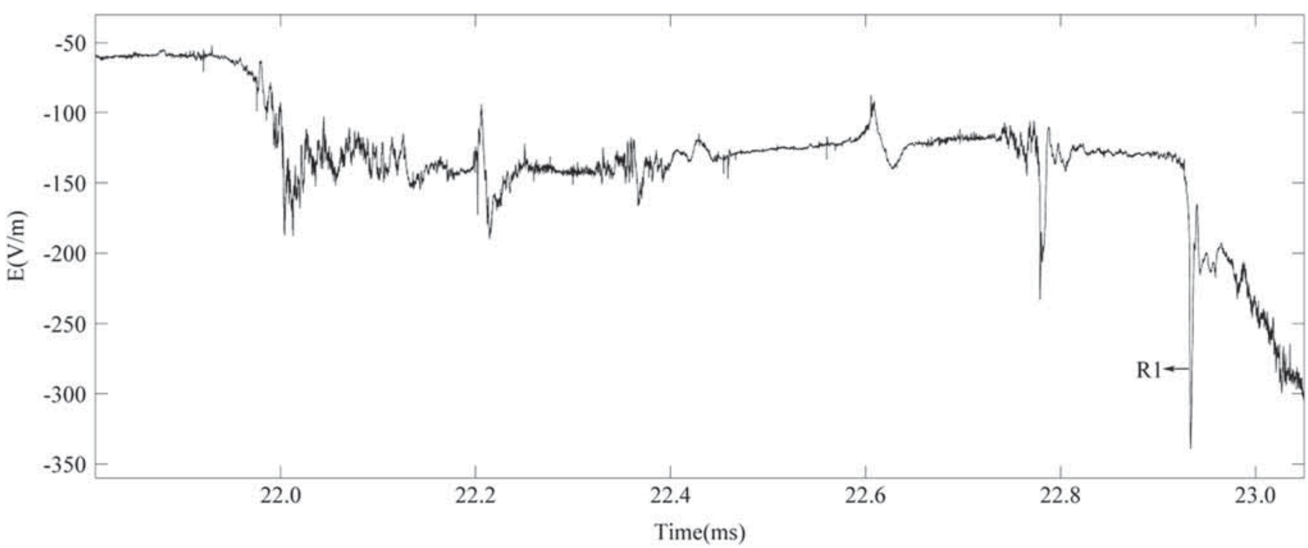

Figure 3. Electric field change of the subsequent return stroke R1 for lightning A.

pulse at 22.784 ms. The subsequent return stroke R1 takes place at about 22.938 ms (figure 2j). According to the developing feature of the channel and the corresponding electric field changes, lightning A may be formed from a cloud branch, which accords with the conclusion reported by Thottappillil and Uman (1993).

M components are transient perturbations during the relatively steady continuing current that follows the return stroke pulse associated with channel luminosity (Rakov and Uman 2003). Based on the electric field data and optical images, the five components have been defined. Figure 4 shows the luminous channels of the subsequent return stroke R1 and five M components for lightning A, which corresponding to the electric field change waveform in figure 1. Unlike the other four M components, the luminous intensity of M5 is mainly in the horizontal channel, it should be related to the formation of lightning A, which is initiated from a branch of intracloud discharge. Compared with the horizontal channel in figure 2b, c and j, it also can be seen that the M5 should take place exactly in the same horizontal channels as the initial intracloud discharge. Table 1 shows the discharge parameters of R1 and the following M components for lightning A. E is the initial peak value of the electric field change normalised to 100 km. t_{i} is the time interval between adjacent electric field pulses and I is the peak current.

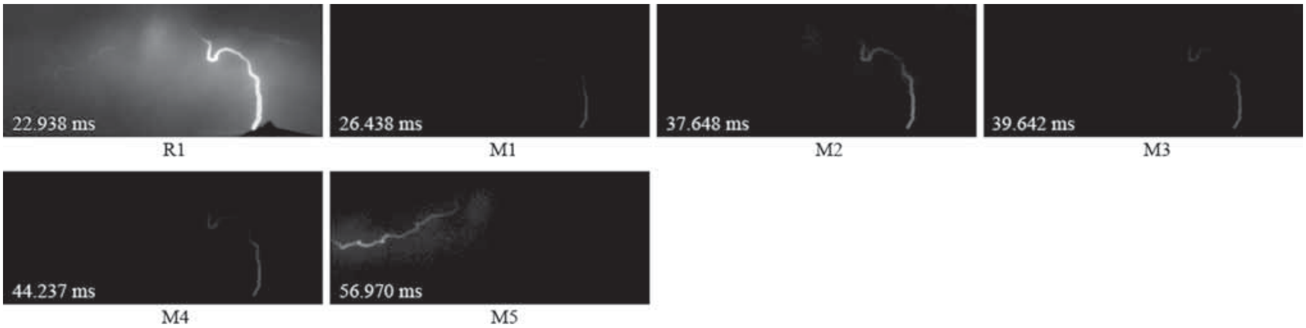

Figure 4. Luminous channels of the subsequent return stroke R1 and the five M components for lightning A. The time of five M components is given in the graph.

Table 1. *Discharge parameters of R1 and M components for lightning A.*

A	t_i (ms)	E (V/m)	I (kA)
R1		5.560	18.60
M1	3.50	0.254	0.848
M2	11.21	0.404	1.350
M3	1.994	0.218	0.725
M4	4.595	0.283	0.944
M5	12.733	0.713	2.380

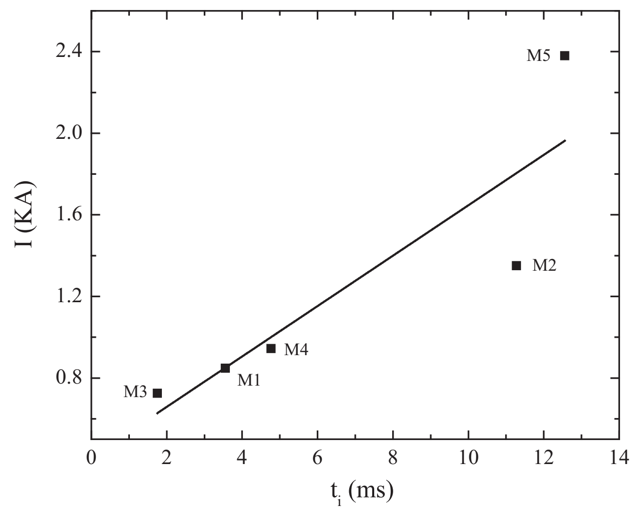

Figure 5. Relationship between the peak currents and time interval of M components. R0 indicates the first return stroke, R1 indicates the subsequent return stroke. Such as A (R0) represents the first return stroke of lightning A.

It can be shown from table 1 that the maximum peak current of M components is about 2.38 kA, corresponding to the discharge of M5 in the horizontal channel. Thottappillil *et al.* (1995) reported that the peak current for M components of negative CG lightning was only a few hundred amperes. But Rakov *et al.* (1998b) found that the peak current of a small number of M components can reach several thousand amperes. The peak currents of the return stroke and M component for positive CG lightning A are all greater than the values of common negative CG lightning. Available data suggest that the M component peak current in positive lightning can be much higher (in the tens of kiloamperes range) than the typical values (up to a few kiloamperes) observed in negative lightning (Rakov and Uman 2003).

Figure 5 shows the relationship between the peak currents and the time interval of M components for positive CG lightning. It can be seen that there is a roughly positive correlation between the time interval and peak current, such as the longer the time interval between M4 and M5, the larger the peak current of M5. This characteristic is similar to the correlation between the time interval and the peak current of the return strokes (Thottappillil *et al.* 1992; Cooray and Pérez 1994).

3.2.2 *Characteristic parameters of the return stroke channel for positive CG lightning*

Spectra pictures for the whole discharge channel outside the cloud of two positive CG lightning return strokes were recorded using a high-speed camera. For quantitative analysis, some excellent positions with good spectrum resolution along the channel are selected, and the pictures are converted into spectral graphs expressed by the relative intensity of the spectral line.

Figure 6 shows the spectral graphs on one of the positions along the channel for lightning A(15:46:40) and B(15:44:28). Figure 6a and c is the spectral graphs of the first return stroke R0 for lightning A and B, figure 6b is the spectral graph of the subsequent return strokes R1 of lightning A. The abscissa and ordinate represent the wavelength and relative intensity of the spectral lines,

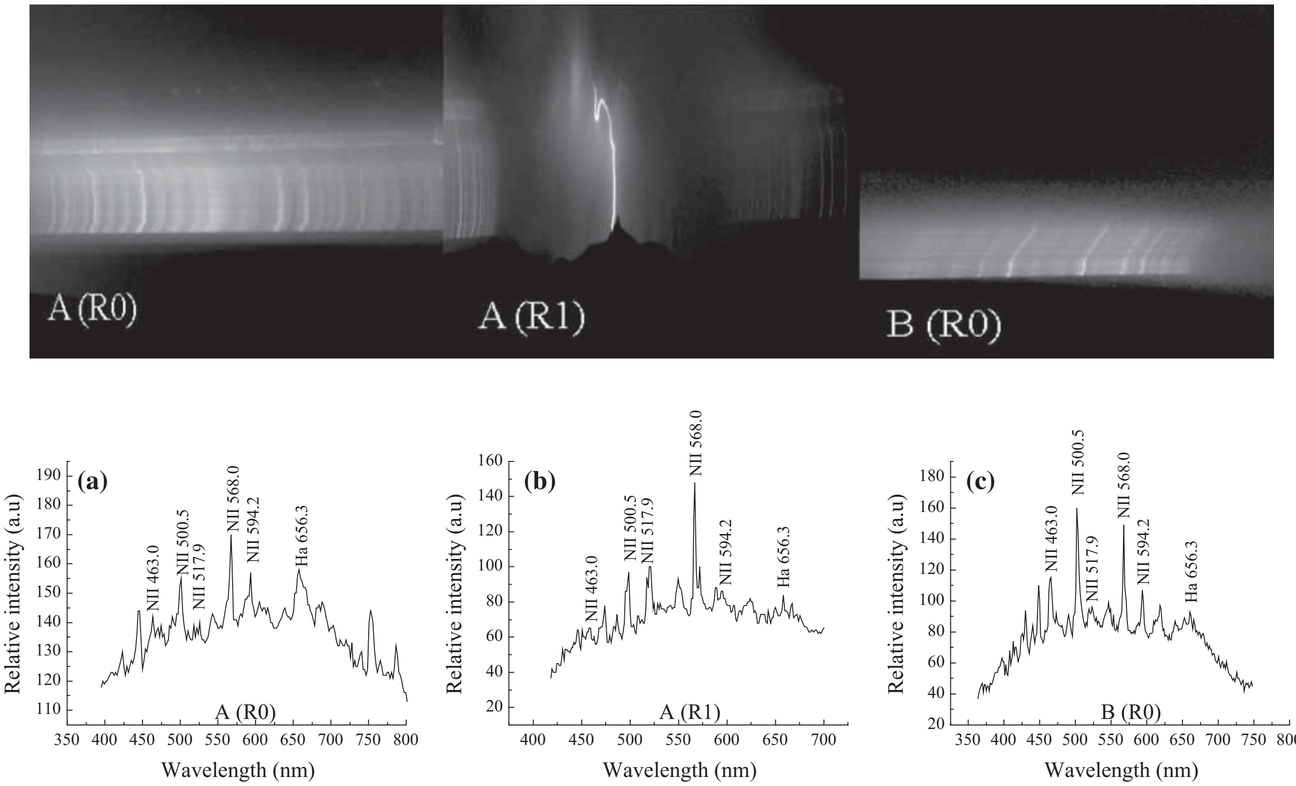

Figure 6. Original spectral images and corresponding spectral graphs of lightning A(15:46:40) and B(15:44:28). R0 indicates the first return stroke, R1 indicates the subsequent return stroke. Such as A (R0) represents the first return stroke of lightning A.

Table 2. *Physical parameters of return stroke for positive lightning A and B.*

Return stroke	D (km)	T (K)	σ (10^4 S/m)	E (V/m)	I (kA)	r (cm)
			A			
R0	12.5	29,600	2.2	11.38	38.0	1.01
R1	12.5	28,900	2.3	5.56	18.6	0.36
			B			
R0	13.9	29,800	1.9	8.87	29.6	0.98

respectively. Like the spectrum of the negative CG lightning return stroke (Cen *et al.* 2015), the spectral lines of positive CG lightning return stroke are mainly composed of nitrogen (NII) ionic radiation in the visible range and neutral nitrogen, oxygen (NI and OI) radiation in the near infrared range. The ionic lines and neutral atom lines should be radiated from the different radial positions of the channel (Wang *et al.* 2016a), and the NII radiations mainly from the current-carrying channel core have been analysed by Uman and Orville (1965). Because the location of the channel is not right in front of the spectrograph, the spectrum in the infrared band is outside the field of view. Figure 6 only shows the spectrum in 400–700 nm. During practical calculation, these lines of NII with 463.0, 517.9, 568.0 and 594.2 nm are used to calculate the temperature of the core channel by the linear fitting of (1).

Table 2 lists some physical parameters of each return strokes for two positive CG lightning. Here, D is the estimated horizontal distance between the lightning channel and the observation site. Average temperatures (T) and conductivity (σ) can be obtained by using spectral information and formulas (1) and (2). E is the initial peak of the corresponding electric field change of the return stroke normalised to 100 km, I is the peak current of the return stroke. r is the radius of the core current channel. In table 2, the average temperature of two positive CG lightning channels is about 29,400 K, which is slightly higher than the value of the normal negative CG lightning (Cen *et al.* 2015; Dong *et al.* 2017). The temperature of positive return strokes channel calculated by Prueitt (1963) ranges are from 24,200 to 28,400 K. The electrical conductivity is closely related to the plasma temperature. As shown in table 2, the conductivity of the return stroke channels for positive lightning A and B are in a range of $(1.9–2.3)\times10^4$ S/m, which is consistent with an estimate of 10^4 S/m order of magnitude reported by Rakov (1998a) for negative lightning. The values for negative discharge channels reported by Guo *et al.* (2009) are in a range of $(1.62–2.27)\ \times10^4$ S/m. The peak currents of the first return strokes for lightning A and B are 38.0 and 29.6 kA, respectively. The value of the subsequent return stroke for lightning A is 18.6 kA, which is obviously smaller than that of the first return stroke. According to USA National Lightning Location Network data, Nag and Rakov (2012) found that the peak current of positive CG lightning is in the range of 20–234 kA with a geometric average of 75 kA. In one example reported by Brook *et al.* (1980), the average current of a positive ground flash is 70 kA. The average peak current values for negative and positive flashes were 29.90 and 63.97 kA, respectively (Sonnadara *et al.* 2006). The radius of the core current channel for the two positive CG lightning are in the range of 0.36–1.01 cm, which is larger than the reported value of 0.2–1.0 cm for negative CG lightning (Wang *et al.* 2013). According to the dynamics of lightning channel corona sheath (Maslowski and Rakov 2006, 2013), lightning channel comprises a fully ionised current carrying core and an external corona sheath. The diameter of the channel core is positively proportional to the current flowing through it (Borovsky *et al.* 1998; Wang *et al.* 2014). Wang *et al.* (2016b) analysed multiple return strokes negative CG lightning, and found that there is a good linear relationship between the radius of the core current channel and the peak current. Roughly from table 2, such correlation should also be established for positive CG lightning.

4. Conclusions

According to the spectra and synchronous electric field change data, the characteristic parameters of three return strokes for two positive CG lightnings have been obtained. Their peak currents are about 18.6–38.0 kA. The average temperature, electric conductivity and radius of discharge channels are about 28,900–29,800 K, $(1.9–2.3)\ \times10^4$ S/m and 0.36–1.01 cm, respectively, which are all larger than the average value of the usual negative CG lightning. There is a positive correlation between the peak currents of M components and the time intervals between five M component pulses which overlapped with the continuous current.

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