AIP Journal of Applied Physics

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Citation: Journal of Applied Physics **114**, 163303 (2013); doi: 10.1063/1.4827182
View online: http://dx.doi.org/10.1063/1.4827182
View Table of Contents: http://scitation.aip.org/content/aip/journal/jap/114/16?ver=pdfcov
Published by the AIP Publishing

JOURNAL OF APPLIED PHYSICS **114**, 163303 (2013)

Characteristics and applications of near-infrared emissions from lightning

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(Received 24 July 2013; accepted 10 October 2013; published online 28 October 2013)

Using the lightning spectra captured by a slitless spectrograph, the characteristics of near-infrared emissions from lightning are investigated. The results show that atomic lines in the near-infrared range are consistently strong and can be almost recorded during the whole luminous phase from the leader to the return stroke. OI 777.4 nm is persistently one of the strongest lines in the near-infrared range of lightning spectra. Moreover, by combining synchronous electric field information, the intensity of OI 777.4 nm is found to correlate well with the amplitude of the electric field change, and its waveform is consistent with the waveform of synchronous electric field change. It is concluded that the information of OI 777.4 nm recorded in the thunderstorm activities can be used to locate the lightning discharge processes, including counting the flashes, identifying discharge intensity, displaying spatial and temporal evolution of the discharge channel, and even presenting more details of discharge processes. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4827182]

I. INTRODUCTION

Lightning detection and location, which are important for research of lightning physics and design of lightning protection systems, have been a focused topic in the field of thunderstorm physics for decades. At present, lightning location are largely based on electromagnetic pulses radiated from lightning.[1–5] Measurements from ground-based multiple stations distributed in a certain area can determine the three-dimensional structure of channels and the discharge characteristics of lightning. However, due to limited number of stations, the observations from multiple stations on the ground cannot monitor lightning activities in more large-scale territorial scope.[6–9] While observations for lightning from satellites can cover wide regions and even the whole earth, and they are mainly based on optical signals.[10–12] Optical measurements for lightning hold an advantage of directly displaying geometric features of lightning channel and its development with time. Besides, luminosity properties of lightning channel are closely correlated with discharge characteristics of lightning. The correlativity between optical signals and electric field change radiated by the same strokes has been analyzed by Guo and Krider,[13] Jordan and Uman,[14] and Light *et al.*[15]

Measurements from NASA U-2 airplane have shown that the dominant radiation peaks of lightning are atomic lines in the near-infrared range, where OI 777.4 nm is one of the strongest lines among them.[16–19] Goodman *et al.*[17] and Koshak[20] have discussed pulse structures, radiances and energy of first stroke, subsequent strokes and intracloud components (K-changes) by detecting 777.4 nm from an airplane and satellite. Kirkland *et al.*[21] presented the statistical variation of the peak power of cloud-to-ground lightning from measurements at 777.4 nm at 20 km altitude. Based on optical measurements for 777.4 nm from the FORMOSAT-2 satellite and simultaneous ground-based magnetic field measurements, Frey *et al.*[22] investigated the leader processes of elve-producing lightning. Up to now, the correlation between OI 777.4 nm and lightning discharge characteristics has not been researched, and this is the purpose of the present work. In addition, Brook *et al.*[18] and Christian *et al.*[23] have shown that lightning spectra and electric-field-change data of lightning discharge processes recorded from the cloud top are quite similar to ground-based measurements. And a sensor in geostationary orbit is capable of monitoring both spatial and temporal evolution of lightning activity during daytime and nighttime. Therefore, it is necessary and significant to apply our research results obtained from the ground-based stations to space to investigate global thunderstorm activities.

In this paper, using lightning spectra, the characteristics of near-infrared emissions produced from lightning processes are investigated. In combination with synchronous electric field information, the correlations among the intensity of OI 777.4 nm, the amplitude of electric field change, and the electric field change waveforms are analyzed in detail. Finally, the feasibility of realizing a new kind of lightning locating system by observing OI 777.4 nm from satellites is discussed.

II. INSTRUMENTATION

Lightning spectra were captured by a slitless spectrograph, and its recording system was a digital video camera

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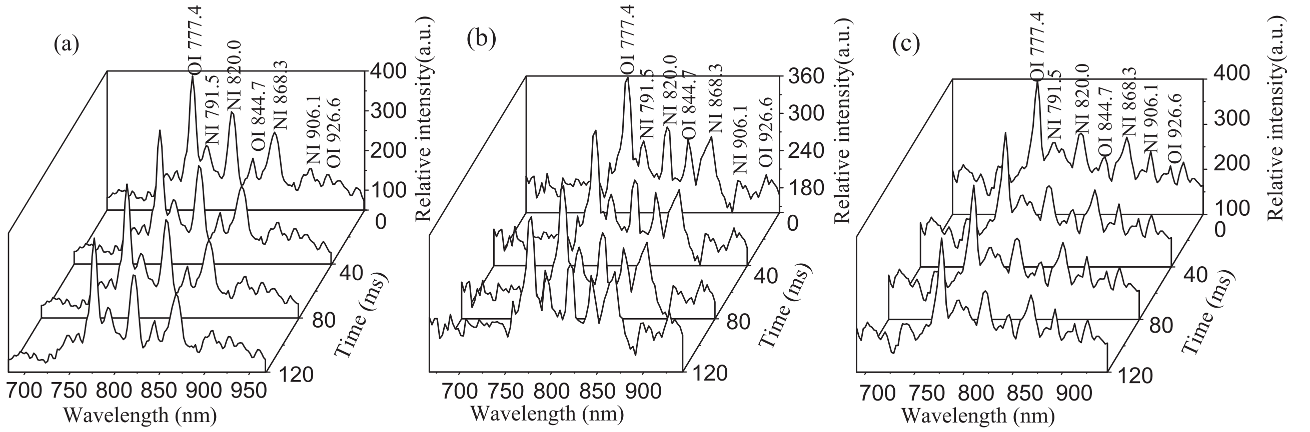

FIG. 1. The spectra of three flashes, (a) lightning 22:13:58, (b) lightning 23:10:26, and (c) lightning 23:14:01, represented by the relative intensity distributions of lines at a typical position along the discharge channel.

or high-speed video camera. A transmission grating of 600 lines mm^{-1} was put in front of the object lens. The digital video camera was operated at 50 frames per second (fps) with exposure times of 10 ms per frame. Exposure times of the high-speed video camera with 1280×400 pixel resolution were 333.3 μs (3000 fps). The synchronous electric field information on the ground was obtained by slow antenna and fast antenna.

III. DATA ANALYSIS

Near-infrared spectra of three flashes in Shandong province of China were recorded with a digital video camera. There are eight images obtained for every flash. The total duration of every flash is about 160 ms. Named by their occurring times (Beijing time), respectively, the flashes are 22:13:58, 23:10:26, and 23:14:01. For quantitative analysis, some well differentiable positions along the channel are selected, and the images are transformed into spectrum graphs which are represented by the relative intensity distributions of lines. The spectra of each flash at intervals of 40 ms are presented in Fig. 1.

Figure 1 shows that the discrete spectra are dominantly emitted by OI and NI. Flashes 22:13:58 and 23:10:26 are cloud-to-ground lightning, and 23:14:01 is a cloud lightning. It can be seen clearly from Fig. 1 that the changes of spectral structure of every flash with time going on are very tiny. There are only few differences among the flashes with different discharge intensities and types. Figure 2 presents the variations in intensity of four lines (777.4, 820.0, 844.7, and 868.3 nm) from the spectra of three discharge channels. It indicates that the near-infrared emissions from lightning are very strong and have a long duration (about 120 ms). One of the reasons to get the above-mentioned results is the long exposure times (10 ms) and low photosensitivity of the digital video camera, which makes it not record the detailed changes during lightning discharge processes. Even so, Figs. 1 and 2 still indicate that near-infrared emissions from lightning are persistent and stable. Meanwhile, the near-infrared range belongs to one of the atmospheric windows, therefore they are easily detected. Based on the above characteristics, even if a low time-resolved detector is used, it can count and locate lightning.

In order to further explore the characteristics of near-infrared emissions, lightning 18:06:58 is analyzed, which is recorded by a high-speed video camera with higher photosensitivity (ISO-12232SAT, 13000) in Qinghai plateau in July 2012. It consists of nine return strokes and its entire duration is about 312 ms. R0 represents the first return stroke of lightning, and R1 to R8 represent the subsequent strokes. Two images are captured for stroke R0, R1, R2, and R4, respectively; three images are captured for stroke R3 and R8,

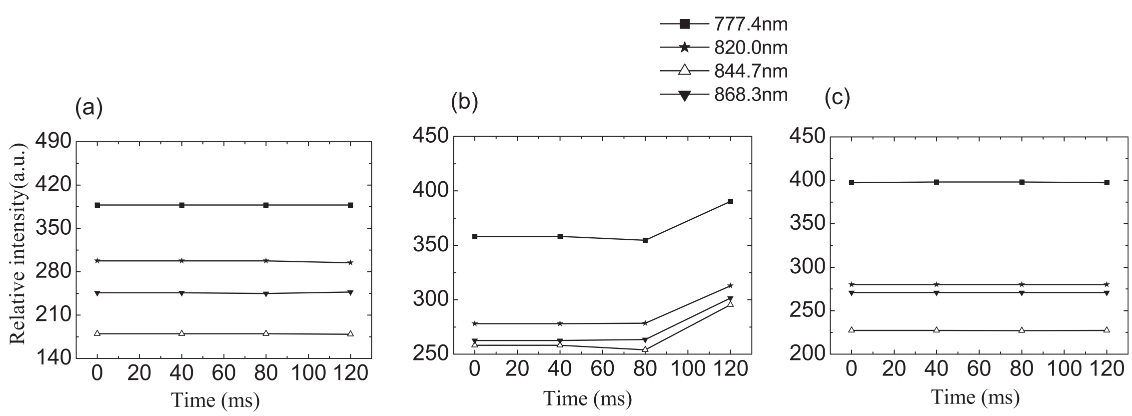

FIG. 2. The intensities of four lines from the near-infrared spectra versus time: (a) lightning 22:13:58; (b) lightning 23:10:26; (c) lightning 23:14:01.

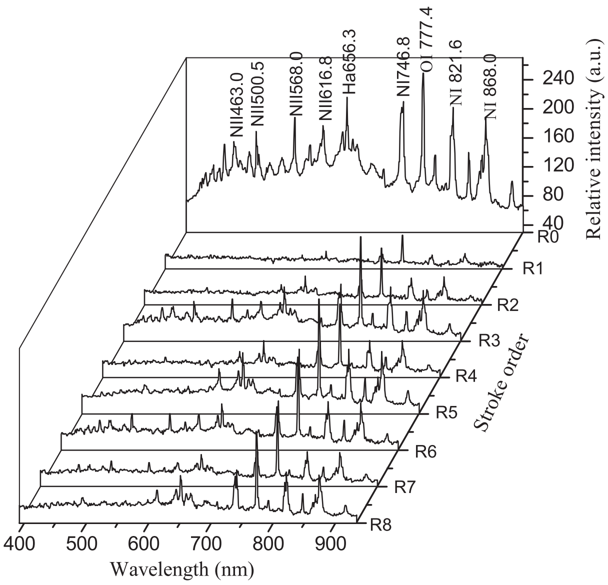

FIG. 3. The spectra of nine return strokes of lightning 18:06:58.

respectively; four images are captured for stroke R5; and one image is captured for stroke R6 and R7, respectively. The first spectrum of every return stroke is shown in Fig. 3.

In general, the total spectral intensity (the background intensity of spectra plus the intensity of lines) of the first return stroke is the largest in a lightning.[24] The point is again verified in this work. In Fig. 3, the total spectral intensity of R0 is the largest, and those of R3 and R5 are inferior to R0, and that of R1 is the smallest. The common features of the near-infrared range of the spectra in Fig. 3 are that the strong discrete lines are superimposed on the relatively weak continuous spectra. While in the visible range of the same spectrum the continuous spectra are stronger, and the discrete lines are merely strong at the peak of the discharge current. Figure 3 also shows that OI 777.4 nm is consistently strong in nine return strokes of lightning 18:06:58, which agrees with the results of Fig. 2.

To study the characteristics of near-infrared emissions during the individual stroke process, Figs. 4 and 5 display the spectra of the stroke R3 and R5 processes, respectively. In general, the return-stroke current reaches to the peak value from zero in several microseconds, and then descends slowly. Since the total intensity of the spectra is positively correlated to the strength of the discharge current.[25] The total intensities of three spectra in Fig. 4 decrease gradually as time evolves, which correspond to the decay phase of the current. It can also be seen from Fig. 4 that OI 777.4 nm becomes weak gradually, but in the three spectra of stroke R3 it is always stronger than other lines, including NII 500.5 nm, which is an intense line in the visible range. Figure 4 indicates that the atomic lines in the near-infrared range remain longer than the singly ionized lines in the visible range. It is inferred from the feature of spectra that Fig. 5(a) is a spectrum of leader,[26] while Figs. 5(b)–5(d) correspond to the decay phase of the current of the stroke R5. Figure 5 confirms that OI 777.4 nm appears from the leader to the end of the return stroke and is consistently stronger than other lines.

The research has confirmed that the total intensity of spectra correlates closely with the peak value of the electric field change.[25,27] Figure 6 displays the intensity of OI 777.4 nm and the total intensity of the first spectra of every return stroke in lightning 18:06:58. The corresponding slow

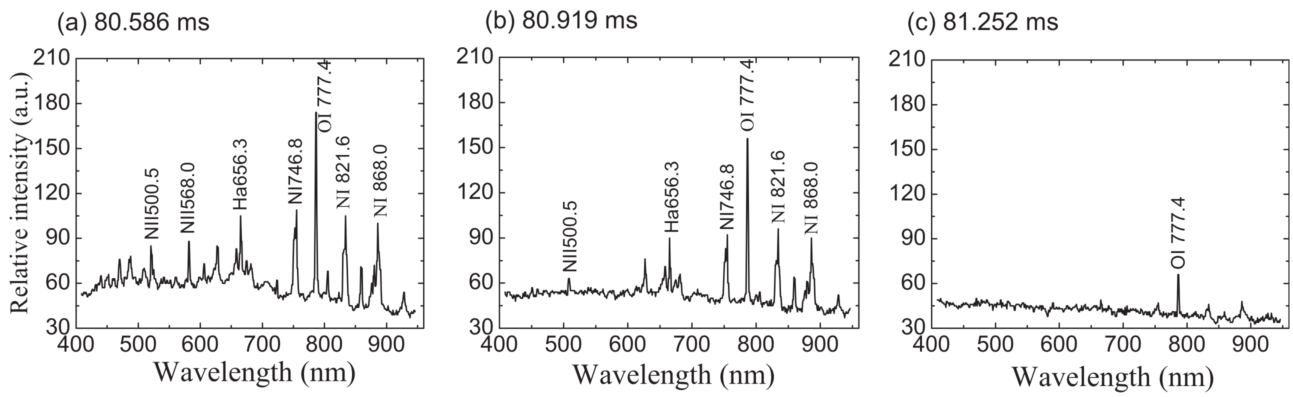

FIG. 4. Spectra of stroke R3 process of lightning 18:06:58.

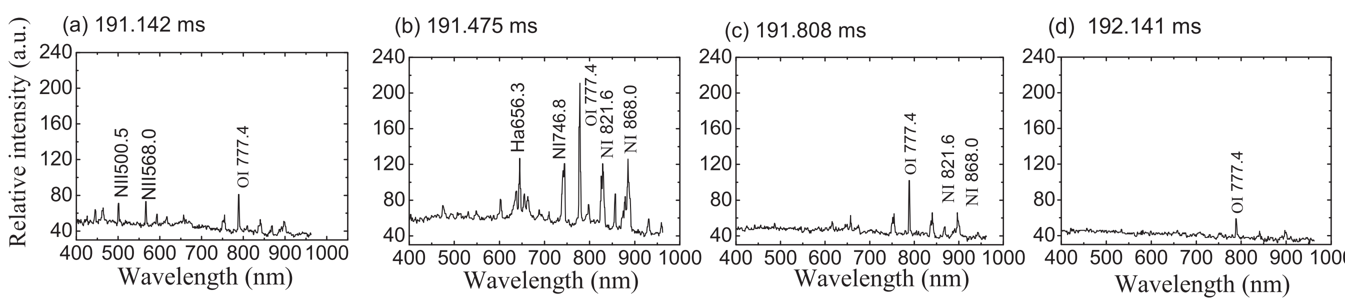

FIG. 5. Spectra of stroke R5 process of lightning 18:06:58.

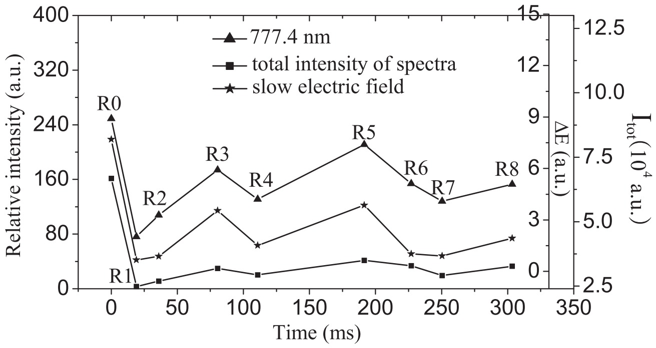

FIG. 6. The relative intensity of OI 777.4 nm, the total intensity (I_{tot}) of the first spectra of every return stroke, and electric field changes (ΔE) from lightning 18:06:58.

electric field changes are also given in Fig. 6. The intensity of OI 777.4 nm is positively correlated to the amplitude of the electric field change in Fig. 6. In return stroke R0, when the amplitude of slow electric field change is the largest, and the intensity of OI 777.4 nm is also the largest; in return stroke R1, the amplitude of slow electric field change is the smallest, and the intensity of OI 777.4 nm is also the smallest. Generally, the peak of optical signal is delayed by tens to a few hundreds of microseconds from the peak of electric field change.[13,15] Though the peak of OI 777.4 nm and the peak of electric field change do not come forth simultaneously, for the individual stroke, their evolution trends present a good consistency in the discharge progresses. Therefore, characteristics of lightning discharge can be deduced from intensity change of OI 777.4 nm recorded by an optical sensor.

Figure 7 further displays slow and fast electric field change waveforms and the intensity of OI 777.4 nm for lightning 18:06:58. It suggests that the intensity of OI 777.4 nm is well correlated to fast electric field change waveform, but the correlation coefficient need to be further calibrated. If more highly time-resolved and more sensitive detectors are used, the more elaborate curves of the variation in intensity of OI 777.4 nm, which are similar to Fig. 7(c), are anticipated to reflect detailed and tiny discharge processes including M component, K event, and so on. In addition, OI 777.4 nm received by the optical detector can directly presented the geometrical growth of the discharge channel with time. Based on the above-mentioned characteristics, it is expected to realize a new kind of lightning locating system by observing OI 777.4 nm. And this system can be applied to satellites to study the physics characteristics of lightning process on a global scale.

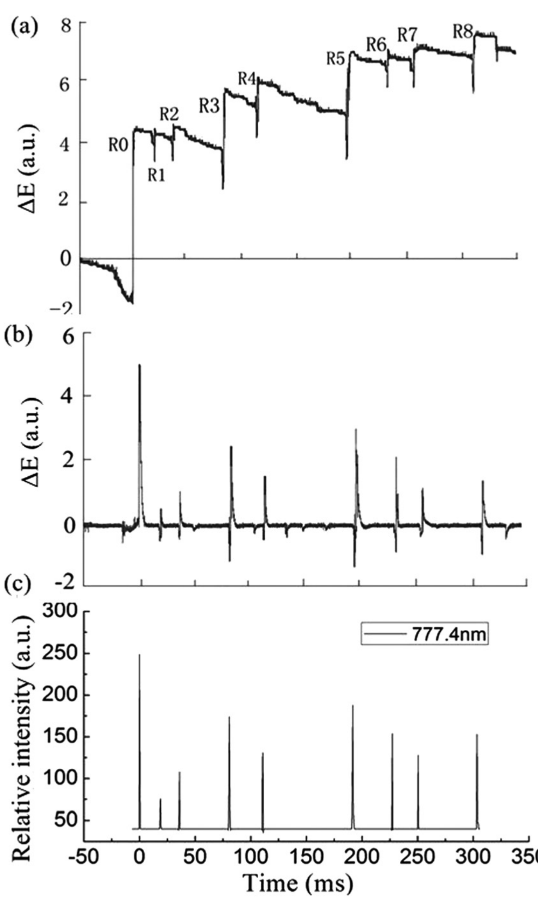

FIG. 7. Electric field change waveforms monitored by (a) slow antenna, (b) fast antenna, and (c) the relative intensity of OI 777.4 nm.

IV. CONCLUSION

Spectral line OI 777.4 nm is intense and can be observed in the spectra from the leader to the return stroke of a lightning. The intensity of OI 777.4 nm is positively correlated to the waveform of the electric field change in a lightning process. Based on these features, observations for OI 777.4 nm from satellites is expected to realize a new kind of lightning locating system.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation of China under Grant No. 11365019 and by Open Fund of Key Laboratory of Environmental Optics and Technology of Chinese Academy of Science under Grant No. 2005DP173065-2013-01.

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