Observation of the Optical and Spectral Characteristics of Ball Lightning

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(Received 26 April 2013; revised manuscript received 13 November 2013; published 17 January 2014)

Ball lightning (BL) has been observed with two slitless spectrographs at a distance of 0.9 km. The BL is generated by a cloud-to-ground lightning strike. It moves horizontally during the luminous duration. The evolution of size, color, and light intensity is reported in detail. The spectral analysis indicates that the radiation from soil elements is present for the entire lifetime of the BL.

DOI: 10.1103/PhysRevLett.112.035001 PACS numbers: 92.60.Pw, 52.80.Mg

Introduction.—Ball lightning (BL) is a mysterious and rare phenomenon that has attracted the attention of scientists for centuries [1–6]. The features of BL are mainly based on the reports of eyewitnesses. Typically, ball lightning is associated with thunderstorms, either immediately after a cloud-to-ground (CG) lightning strike or while lightning activity is present in the vicinity. It is usually observed within close range of the ground, in the shape of sphere or ellipsoid with a diameter between 1 and 100 cm, moving horizontally with speeds of a few meters per second. The lifetime can range from 1 to 10 s and the color can be white, yellow, red, orange, purple, or green.

Many different models and experiments proposed to explain and reproduce BL, which can generally be divided into two classes, according to whether the energy source is internal or external. The most recent of the internal-energy theories was proposed by Abrahamson and Dinniss [7], suggesting that BL is ejected by a CG lightning striking the soil, in the form of filamentary networks. The slow oxidation of silicon nanopartics provides the internal energy for its existence. In support of this theory, Paiva *et al.* [8] reported that electric arc (the voltage is in the range of 20–25 V, the current varies from 100 to 140 A, and the frequency is 60 Hz) discharges in pure silicon can generate luminous balls with several of the properties usually reported for natural BL. The apparent diameters of these luminous balls are in the range of 1–4 cm. The color of bright bluish white or orange white can be seen during the lifetime of 2–5 s. Immediately, Stephan and Massey [9] carried out the similar experiment, producing silicon-based luminous balls with diameters of 0.1–1 mm. The estimated temperature of these balls is about 3140 K. For external-energy theory, Lowke *et al.* proposed that BL is regarded as a pulsed electric discharge with frequency on a microsecond time scale, which can provide an explanation for the formation, lifetime, energy source, and motion of natural BL [10,11]. The most well-known model was proposed by Kapitza [12], hypothesizing that an intense radio frequency electromagnetic field could supply the necessary energy to form and sustain BL. A great number of microwave experiments leading to the generation of fireballs have been conducted based on this model [13–16]. Recently, Dikhtyar and Jerby [17] reported the ejection of fireballs from molten hot spots induced by localized microwaves. These fireballs with diameters of about 3 cm can last 30–40 ms after the microwave power was turned off and their colors range from yellow to red. Moreover, Dikhtyar and Jerby considered that the experimental observations of fireball ejection from silicate hot spots are referred to the Abrahamson-Dinniss theory [7] suggesting a generation of natural BL.

In this Letter, the observation of a natural ball lightning generated by a cloud-to-ground lightning strike is reported. The optical and spectral characteristics of the BL have been presented in detail, which suggest the origin and composition of the BL.

Instrumentation.—In the summer of 2012, at Qinghai Plateau of China, when we were carrying out the experiment on spectrum of natural CG lightning with two slitless spectrographs, the BL occurred accidentally. Each slitless spectrograph consist of a camera and a plane transmission grating with 600 lines/mm in front of the objective lens. The two cameras including a high-speed camera (M310) and a digital video camera (NV-GS400GC) were placed in the same observation site and were matched by GPS time synchronization. Their fields of view were gradual hills where CG lightning frequently occurred. The altitude of observation site (37.013473 °N, 101.620080 °E) is about 2530 m. The highest altitude of the hill is about 200 m higher than the observation site. The high-speed camera with the lens of 20 mm focal length takes black and white photos, was operated at 3000 frames per second (fps) with the exposure time of 333.32 μs and spatial resolution of 1280×400 pixels (each pixel is 20×20 μm^2 in size). Its recording duration was 1.11 s. The spectral response range of the camera is from 400 to 1000 nm, and the wavelength resolution is about 1.1 nm. The digital video camera with the lens of 3.3 mm focal length takes color photos, was operated at 50 fps with a spatial resolution of 640×480 pixels (each pixel is 4×4 μm^2 in size). It continuously recorded images using 2 ms exposure time per frame. Its spectral response range is from 400 to 690 nm, and the wavelength resolution is about 1.8 nm for the first-order spectrum.

Results.—The BL occurred during a thunderstorm at 21:54:59, 23 July 2012 (Beijing Time). The digital video camera recorded its entire process, including video, sound, and 82 still images. The entire luminous duration of the BL is 1.64 s. The first image is presented in Fig. 1(a), showing the generation of the BL from the bottom of a CG lightning channel. The first-order spectrum and second-order spectrum of the CG lightning channel and the BL are also recorded. The second image is presented in Fig. 1(b), which is recorded 20 ms later. It can be seen that the CG lightning channel has disappeared and only the BL exists. More images of the BL, as recorded by the digital video camera, are provided in the Supplemental Material Fig. 1 [18]. The high-speed camera only recorded the latter period of the BL process due to the limit of its recording duration, and there are about 2360 still images captured in 0.78 s. A selected black and white image showing the BL and first-order spectrum is presented in Fig. 1(c). Since the BL occurred at night, the background was too dark to see the location of the lightning strike point in all recorded images. However, it is pinpointed by a photo taken in daylight with the same field of view of the digital video camera, which is showed in the Supplemental Material Fig. 2 [18] based on Google Maps. The center of the BL location area is about 0.902 km (with error of ± 0.0077 km) away from our observation instruments. Meanwhile, according to the speed of sound ($340.51 - 341.15$ m/s, the air temperatures in the propagation path of sound are in the range of 14–15 °C and the relative humidity is 82%) and the time difference (2.64 s) between the lightning strike and the sound, the distance between the observation instrument and the BL is estimated about 0.898–0.9 km, which is consistent with the forenamed distance. Based on the focal length (3.3 mm), the side length of a pixel (4 μm), and the observation distance (0.902 km), the corresponding size for a pixel in the images of the digital video camera is estimated about 1.1 m (horizontal or vertical).

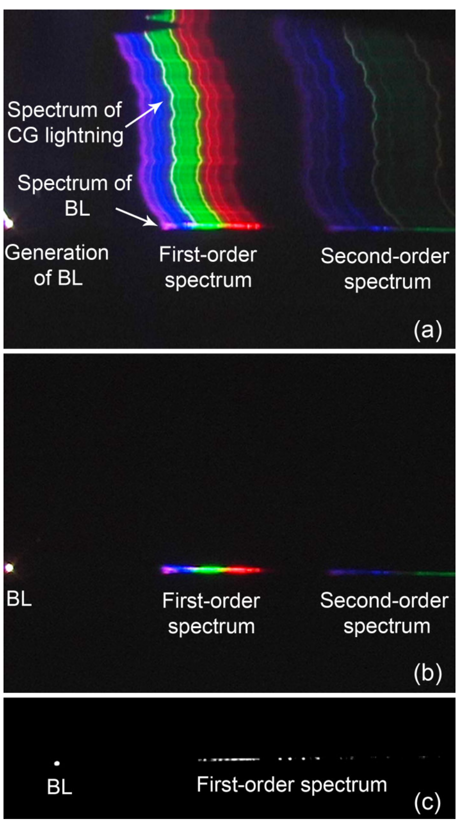

FIG. 1 (color online). (a) The first image of digital video camera showing the generation of ball lightning. (b) The second image of digital video camera. The CG lightning channel disappears. (c) A black and white image of high-speed camera. More color images can be seen in Supplemental Material Fig. 1 [18].

Some magnified images of the BL, recorded by the digital video camera, are provided in Fig. 2. As evident in Fig. 2 and Supplemental Material Fig. 1 [18], the color of the BL varies with time. It presents powerful purple white at the beginning, then changes to orange at 80 ms. It approximately keeps the color of white from 160 to 1100 ms and changes to red at the dissipating stage after 1120 ms. Meanwhile, the change of first-order spectrum of the BL is also consistent with the variation of color (Supplemental Material Fig. 1 [18]). The BL appears to be roughly a spherical shape. The intensity profile across the image shows the peak intensity, the total intensity (area under the curve), and the size, as seen in Fig. 2. The position of the peak intensity corresponding to the center of the BL moves nine pixels in a horizontal direction from 20 ms to 1160 ms, indicating that the average 2D speed of BL is about 8.6 m/s. Considering the BL may simultaneously move in a line-of-sight direction, the actual speed of the BL should be faster than the 2D speed. The full width at half

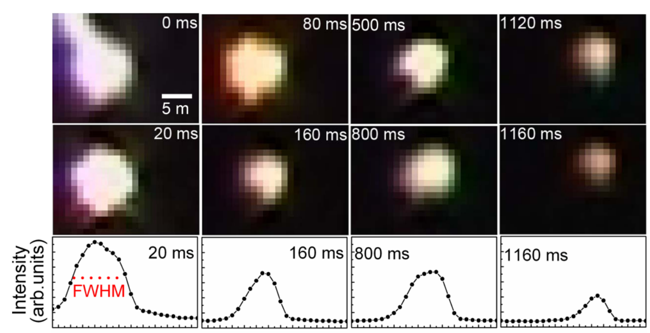

FIG. 2 (color online). Magnified color images of ball lightning in different time. Saturation pixels are not present in the images. The intensity profile across the image is presented below. The abscissa represents the pixel sequence and the vertical ordinate represents the intensity. FWHM represents the full width at half maximum. The side length of a pixel corresponds to 1.1 m in the images.

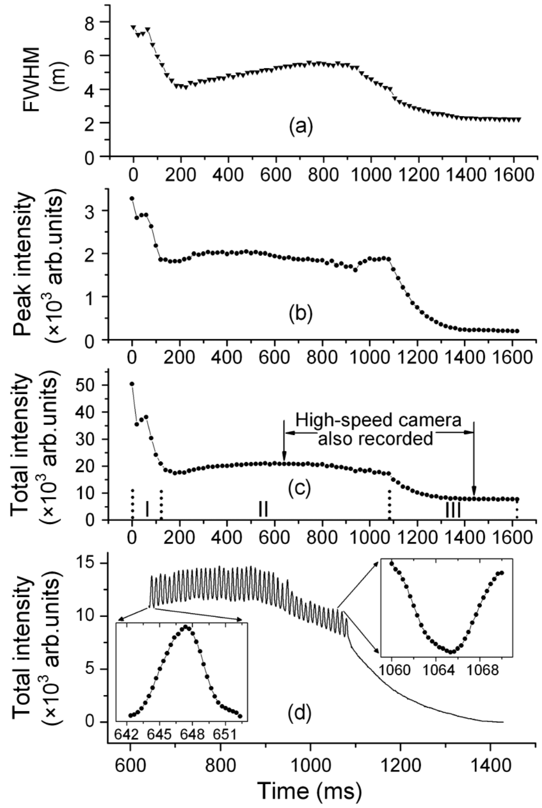

FIG. 3. (a) Evolution of the apparent diameter which is represented by FWHM. (b) Evolution of the peak intensity. (c) Evolution of the total intensity. The data of (a), (b), and (c) are based on the images recorded by digital video camera. (d) Evolution of the total intensity. The data are from the images recorded by high-speed camera. High-speed camera only recorded the later process of the BL.

maximum (FWHM) of the curve is used here to represent the apparent diameter of the BL. The evolutions of apparent diameter, peak intensity, and total intensity are provided in Fig. 3. It is interesting that the evolutionary process consists of three stages which are divided in Fig. 3(c). In the first 160 ms (I), the apparent diameter, peak intensity, and total intensity all decrease greatly except a little increase in the range of 20–60 ms. Then, the peak intensity and the total intensity remain nearly constant at the stable stage (II) with a long time from 160 to 1080 ms, and during this time, the apparent diameter ranges around 5 m. After that, they decrease slowly in the last 560 ms (III) until the BL disappears. On the whole, the color, size, and light intensity do not change much during most of the lifetime (II) of the BL.

Only the later process (642–1440 ms) of the BL has been captured by the high-speed camera. The variation of total light intensity is presented in Fig. 3(d). It can be seen that the light intensity varies periodically with time in the range from 642 to 1080 ms and then decreases during the remaining period. Two cycles are shown on expanded time scales in the inset plots. The times of the two cycles are both 10 ms. Furthermore, every cycle nearly has the same time and the mean value is 10.06 ms.

The images showing the first-order spectrum of the CG lightning and BL are transformed into spectral graphs which are shown in Fig. 4. The abscissa represents wavelength in nanometer and the vertical ordinate represents intensity. The wavelength calibrations are achieved by the characteristic spectral lines [19–21] of the CG lightning. The intensity lacks a calibration. The spectrum of the CG lightning channel is shown in Fig. 4(a), which is in accord with the spectrum of ordinary lightning return stroke

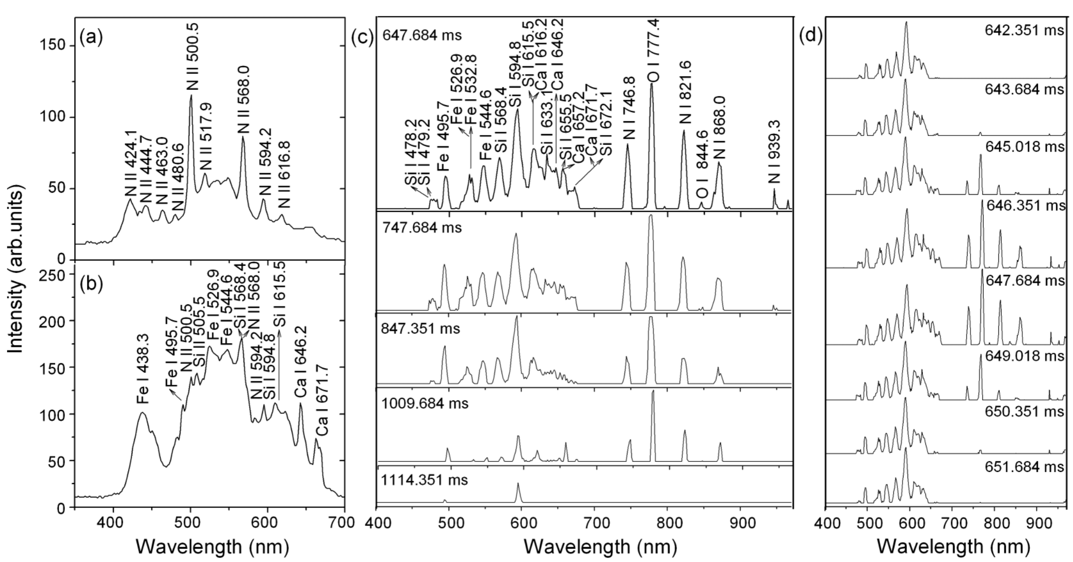

FIG. 4. Spectral graphs showing intensity versus wavelength of CG lightning and ball lightning. (a) Spectrum of the CG lightning channel. (b) Spectrum of the ball lightning at 0 ms. (c) Spectra of the ball lightning in different time from high-speed camera. (d) Changes of the ball lightning spectra in a cycle from 642.351 to 652.351 ms. The cycle consists of 33 spectral graphs, only eight graphs are shown here with a time interval of 1.333 ms.

[22,23]. Due to a high temperature of ~30 000 K in the lightning channel [24], most of the spectral lines are radiated by N II ions. The spectrum of the BL, as presented in Fig. 1(a), is shown in Fig. 4(b). The continuous spectrum is strong, and the emission lines of silicon, iron, and calcium appeared.

The spectra of BL are clearly captured by the high-speed camera which offers higher time resolution and broader spectrum range. Five spectra in different time are showed in Fig. 4(c). The former four spectra are selected corresponding to the peak light intensity of four cycles, respectively. Each spectral line is marked in the 647.684 ms spectrum. In the visible range, most of the emission lines are radiated by neutral silicon, iron, and calcium. It can be seen that the lines of Si I, Fe I, and Ca I exist during most lifetime of the BL, and Si I 594.8 nm is clearly recorded even in the final period. The spectra of the BL in a cycle from 642.351 to 652.351 ms [inset plot in Fig. 3(d)] are shown in Fig. 4(d). In this cycle, the visible lines of Si I, Fe I, and Ca I are present all the time, and their intensities nearly remain invariable. The near infrared lines of N I and O I appear orderly with the increasing of light intensity until their intensities reach the maximum value at 647.684 ms which exactly is the time of the maximum value of light intensity. After that, their intensities decrease gradually with the decreasing of light intensity and they disappear as the opposite order of appearance. Moreover, the same regularity is present in every cycle. Overall, the visible lines of Si I, Fe I, and Ca I are present all the time and the near infrared lines of N I and O I appear periodically in the stable stage.

Discussions.—There may be more than one type of BL and more than one mechanism that explains BL due to the wide range of observed characteristics [6]. Our observation is only one event that may not be representative of all ball lightning. In our observation, the BL and CG lightning channel appear together in a frame [Fig. 1(a)], and the strong emission lines from silicon, iron, and calcium [Figs. 4(b), 4(c), and 4(d)] are detected during the entire process of the BL. It is known that silicon, iron, and calcium are the main components of soil. Consequently, there are reasons to believe that our observed BL is generated by the CG lightning striking to the soil on the ground. In addition, aluminum is also one of the main components of soil. The absence of an aluminum component in the spectra of the BL can be explained as follows. In the BL spectra, the near infrared lines with excitation energies of 11.7–11.9 eV appear periodically [Fig. 4(d)], making the excitation energies of the persistent lines lower than 11.7 eV. The spectral response ranges of the two cameras are 400–690 and 400–1000 nm, respectively. Based on Ref. [25], in the aluminum spectrum, there are no strong lines of Al I in the 400–1000 nm range, and only the strong lines of Al II are present [25]. Yet, the excitation energies of these Al II lines are in the range of 15.0–18.2 eV. Therefore, the aluminum lines are not observed in the spectra of the BL.

The lack of calibration of the spectral line intensity limits our quantitative analysis to the temperature of BL. The variation of temperature may be inferred from the color variation. Wien's displacement law [26] indicates that the objects with higher temperature emit most of the radiation at shorter wavelengths and the objects with lower temperature emit most of the radiation at longer wavelengths. The color varies from purple to orange at 80 ms, which suggests a drop in temperature of the BL. The color is approximately white during the stage II, indicating a constant temperature of the BL, and it is red in the later stage, also inferring a lower temperature at this stage. In addition, spectra of a CG lightning stepped leader could clearly record the persistent lines of NI and OI, even NII [21], and the temperature of stepped leader is in the range from 15 000 to 30 000 K [27]. In contrast, only the lines of N I and O I appear periodically in stage II of BL, indicating that the temperature of the BL should be lower than that of the CG lightning stepped leader.

It is important to note that the apparent diameter is not the real diameter of the BL. The apparent diameter is more correctly referred to the luminance range. The experiment of Stephan and Massey [9] may confirm this point. It is reported that silicon luminous balls have an apparent diameter of 1–4 cm, but they are just illuminated by a liquid core of about 1 mm in diameter.

The observation of the BL may be associated with the Abrahamson-Dinniss theory [7] suggesting a soil lightning-strike mechanism. Besides, it is interesting that the light intensity shows a persistent oscillation during the stable stage. The observed frequency is 99.4 Hz, which is easily associated with the power-line frequency of 50 Hz. As shown in the Supplemental Material Fig. 2 [18], there are a set of high-voltage (35 kV) transmission lines near the location of the BL, and the horizontal distance from the nearest transmission line to the location is about 20 m. This allows us to infer that the fluctuation of the BL in the stable stage is possibly induced by the second-harmonic effect associated with the high-voltage transmission lines.

Conclusions.—The observation of a natural ball lightning has been reported by using two slitless spectrographs. The ball lightning follows closely with a cloud-to-ground lightning strike and moves horizontally with average 2D speed of about 8.6 m/s. The colors of purple, orange, white, and red can be seen in turn during the luminous duration of 1.64 s. In most of the lifetime of the ball lightning, the size has remained approximately constant while the light intensity varies periodically. The radiation from soil elements is present for the entire lifetime of the ball lightning.

We thank the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science, especially Guangshu Zhang, for the help of experimental work. This work is supported by National Natural Science Foundation of China (Grant No. 11365019) and Open Fund of Key Laboratory of Environmental Optics and Technology, Chinese Academy of Science (Grant No. 2005DP173065-2013-01).

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