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Technique for the comparison of light spectra from natural and laboratory generated lightning current arcs

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A technique was developed for the comparison of observed emission spectra from lightning current arcs generated through self-breakdown in air and the use of two types of initiation wire, aluminum bronze and nichrome, against previously published spectra of natural lightning events. A spectrograph system was used in which the wavelength of light emitted by the lightning arc was analyzed to derive elemental interactions. A lightning impulse of up to 100 kA was applied to a two hemispherical tungsten electrode configuration which allowed the effect of the lightning current and lightning arc length to be investigated. A natural lightning reference spectrum was reconstructed from literature, and generated lightning spectra were obtained from self-breakdown across a 14.0 mm air gap and triggered along initiation wires of length up to 72.4 mm. A comparison of the spectra showed that the generated lightning arc induced via self-breakdown produced a very similar spectrum to that of natural lightning, with the addition of only a few lines from the tungsten electrodes. A comparison of the results from the aluminum bronze initiation wire showed several more lines, whereas results from the nichrome initiation wire differed greatly across large parts of the spectrum. This work highlights the potential use for spectrographic techniques in the study of lightning interactions with surrounding media and materials, and in natural phenomena such as recently observed ball lightning. [http://dx.doi.org/10.1063/1.4962205]

Spectroscopy has long been used in the study of natural lightning events, with many techniques having been established between the 1960s and 1980s using traditional film-based photographic methods.[1–9] Modern digital techniques have since been developed and utilized to some extent to give a more accurate insight into natural lightning phenomena.[10–15] By observing the light spectra emitted from a natural lightning arc, studies have demonstrated that both static and time-resolved[16] methods can be used to reveal important information. Each element with which the lightning arc interacts can be identified by a series of well-established and unique wavelengths, a black-body radiation approximation can be used to estimate arc temperature[3,17] with further characteristics, such as pressure,[6] particle and electron density,[6,18] energy,[7] and resistance and internal electric field of the arc,[10] also being derived. However, such techniques have rarely been applied within the lightning laboratory environments, but their realization is expected to offer a greater understanding of lightning interaction mechanisms,[19] notably with recently developed composite materials[20] and related applications.[21] It is also worth noting that such methods are passive, so do not interfere with the lightning arc and are not prone to noise induced by the harsh electromagnetic environment, unlike most electronically based devices, offering further advantages in their use.

Lightning test generators are often designed to replicate the most destructive elements of a lightning event, specifically a current of up to 200 kA delivered within a period less than 200 μs but at a limited voltage;[22,23] a natural lightning event can reach tens of GV whereas a lightning generator typically operates within tens of kV. This restriction means that, in order for the lightning arc to overcome the dielectric strength of the air gap, either the electrode must be placed close enough to the sample surface for the gap breakdown to occur or, more commonly, a thin metallic initiation wire must be used to create a conductive path;[24] the wires are only used to initiate the arc and typically vaporize within a few microseconds.

In establishing spectroscopic capabilities within a lightning laboratory, it is important to investigate how the spectrum of a laboratory-generated lightning arc compares to that of natural lightning, with a particular focus on how this may differ due to the influence of materials within the laboratory test environment with which the arc interacts, such as the electrode materials and initiation wires. It is also important to note that several other major differences exist between natural and generated lightning that could affect the measured results: the average current of natural lightning is around 30 kA, whereas worse case scenarios of 100 kA–200 kA are often used in aerospace for generated lightning; a natural lightning arc may span tens of kilometers whereas generated lightning arcs are only a few centimeters; and natural lightning occurs in a wide range of continuously varying environmental and atmospheric conditions which cannot be reproduced within a laboratory environment. In this work, a natural lightning reference spectrum was first reconstructed from a previously published data. Many such sources exist, with Ref. 2 presenting a comprehensive collection and review of spectra from a number of different natural lightning events. The published spectra were obtained

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using a variety of traditional photographic films across multiple overlapping wavelength ranges with varying light intensity and background levels. While light intensity for both background levels and emission lines across each of the component spectra could not be normalized, the wavelengths of the known atomic lines were sufficient to reconstruct a continuous spectrum from 350 nm (ultraviolet) to 950 nm (infrared). In this work, a series of laboratory experiments were performed to obtain spectra across a similar range from generated lightning, introducing the spectrograph system. A comparison is then carried out to compare the position of the spectral lines.

A 54 kV, 100 kA peak critically damped oscillatory 100 μs duration 18/40 waveform[20] was chosen to represent settings commonly used for testing purposes.[23] A pair of uncontaminated 60 mm diameter vertically aligned hemispherical tungsten electrodes were chosen as this metal is able to withstand the numerous strikes required during experimentation and also because the single tungsten element could later be identified in the spectra results. Although tungsten has many spectral lines across the ultraviolet to infrared region, only a few lines would be prominent enough to show in the resulting spectrum. The distance between the electrodes could be adjusted, and a 14.0 mm separation was used for self-breakdown, as illustrated in Figure 1(a), whereas a 34.0 mm separation, a distance at which self-breakdown could not occur, was used for the initiation wires, as illustrated in Figure 1(b). However, as the initiation wire was tied from one side of one electrode to the opposite side of the other electrode, in order to avoid using any fixings or tapes which may add to the spectra results, the length of the lightning arc was actually 72.4 mm in this case. Two 0.1 mm diameter initiation wires consisting of distinctly different elements were chosen to observe their effects on the resulting spectra: aluminum bronze (CuAl: 84% Cu and 16% Al) and nichrome alloy (NiCrAl: 78% Ni, 14% Cr and 8% Al). The composition of each wire was first confirmed by energy-dispersive x-ray spectroscopy within an electron microscope, and no contaminants were found.

The entire experiment was performed within a light-tight chamber such that the only light detected was from the lightning arc itself. An optic fiber was used to transmit the emitted light to the spectrograph system; it was positioned 2 m from the electrode center vertical axis at a height of 10 mm above the surface of the bottom electrode with a viewing angle of 12°. Focusing lenses and a 1200 line/mm grating with a wavelength range of approximately 140 nm was used to spread the light from the optic fiber into a discrete spectrum that could be centered anywhere within the ultraviolet-visible-infrared wavelength region, although practically this was limited by fiber attenuation and camera sensitivity to 450–900 nm. A CCD digital camera was used to capture the spectrum at a resolution of 0.2 pixels/nm. The spectrograph was calibrated using a mercury-argon laser source and a background image was subtracted from each dataset, with both the light attenuation within the optic fiber and quantum efficiency of the camera taken into account within the resulting spectrum. An illustration of the experimental setup is shown in Figure 2.

The effect of the lightning arc current and arc length on the measured spectrum was considered. A CuAl fuse wire was used between the tungsten electrodes and the spectrograph adjusted to observe the 750 nm–880 nm range where three prominent atomic lines are known to exist: oxygen at 777.4 nm (Ref. 25) and 794.7 nm,[2] and argon at 811.5 nm.[25] However, it was found that lines from the CuAl wire were coincident with the 794.7 nm and 811.5 nm lines altering their expected relative intensity when compared to a natural lightning spectrum. For this investigation, the current magnitude was varied from 30 to 100 kA for an electrode separation of 34.0 mm, resulting in the typically measured spectra as shown in Figure 3(a). Furthermore, using a current of 30 kA, the electrode separation was varied from 34.0 mm down to 14.0 mm, giving a lightning arc length along the initiation wire of 72.4 mm down to 43.2 mm resulting in the typically measured spectra as shown in Figure 3(b). As can be seen from these figures, it was found

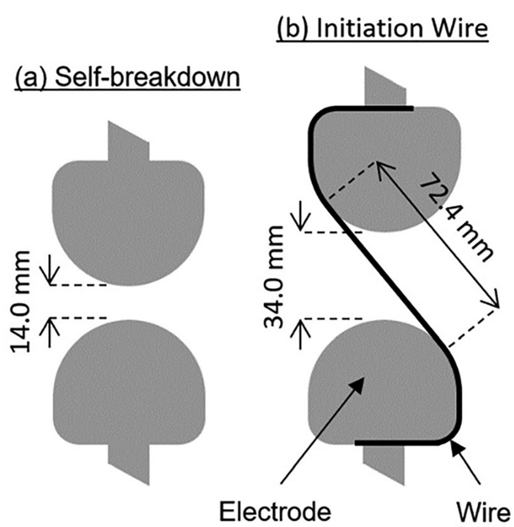

FIG. 1. An illustration of the electrode setup showing (a) a 14.0 mm separation for self-breakdown experiments and (b) a 34.0 mm separation for initiation wire experiments giving a lightning arc length of 72.4 mm along the wire.

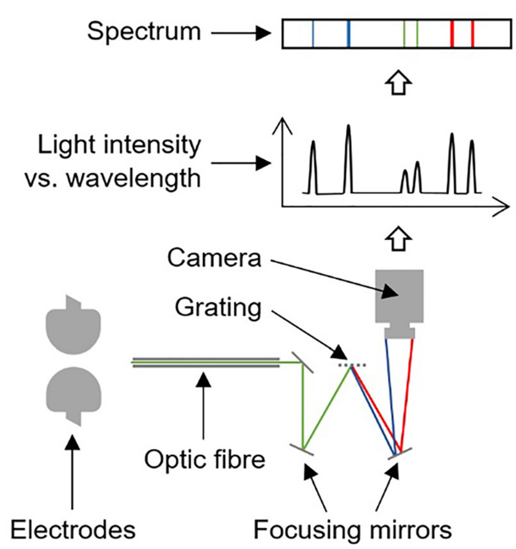

FIG. 2. An illustration of the spectrograph system setup. Light from a generated lightning arc across two electrodes was transmitted via optic fiber and spread along its wavelength via focusing mirrors and a grating into a camera, recording the spectrum.

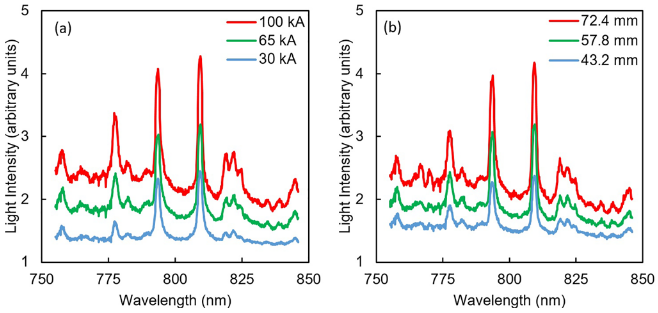

FIG. 3. Measured spectra using the spectrograph technique: The emitted light intensity from a lightning current arc using a CuAl initiation wire varying (a) the lightning arc current magnitude for a 34.0 mm gap and (b) lightning arc length for a 30 kA arc current.

that, although the overall light intensity varies, the position and approximate relative intensity of the spectral lines remain the same in both cases. This was as expected because the spectral lines are characteristic of electrons within the lightning arc interacting with elements within the medium through which it travels, suggesting that the underlying mechanisms for both natural and laboratory lightning arc currents are very similar. Incidentally, an approximately linear relationship between light intensity and increasing current magnitude and arc length could also be deduced. The fact that the position of the spectral lines remains fixed, despite variations in current and arc length, is an important consideration when comparing the resulting spectra, particularly when considering that the natural lightning reference spectrum has normalized light intensity variations due to its reconstruction from previously published data.

Three experiments were carried out to obtain the spectra from a generated lightning arc via self-breakdown and initiated with a CuAl and NiCrAl initiation wire. In each case and starting at 450 nm, four discrete spectra that are approximately 140 nm-wide were measured. The range was then shifted to 550 nm and another four discrete spectra were taken, and this was repeated until 900 nm was reached. Repeatability of the measured results was very good and so each set of discrete spectra could be normalized and averaged, then each was stitched to its neighbors to form a complete spectrum in the 450 nm–900 nm range. Each resulting spectrum was then compared to the others and to the reconstructed natural lightning reference spectrum, as shown in Figure 4, as well as being referenced against known elemental spectra.[2,25] The vast majority of spectral lines were found to be atomic lines such as NI, OI, and ArI, and not higher order ionization states such as NII, OII, and ArII, hence only these are identified and discussed here, with some of the more prominent lines identified in Figure 4. A more comprehensive reference for selected elements can be found in Ref. 2.

The results show that a number of prominent lines are repeated throughout the four spectra due to the lightning arc interacting with air, notably the hydrogen-α line at 656.3 nm, as well as nitrogen, oxygen, and argon lines throughout the spectrum. This is somewhat confirmed by the natural lightning reference spectra within which all of the major lines are due to the elements within the air. Tungsten is also common between the three generated lightning spectra particularly in the 450–600 nm region as was expected from the lightning interacting with the electrodes. The spectrum for self-breakdown in Figure 4(b) shows a very good correlation with that of natural lightning in Figure 4(a) with the addition of tungsten. The use of the CuAl wire in Figure 4(c) introduced several prominent copper lines below 600 nm and a few aluminum lines, with two coincident with the 794.7 nm oxygen and 811.5 nm argon lines, as evident in Figure 3. In this case, the low number of lines present due to the CuAl initiation wire makes it easier to identify the underlying lines present from the air and electrodes. In contrast, in the case of the NiCrAl wire in Figure 4(d), beside the few Al lines, a wide spread of additional nickel and chromium lines up to 780 nm was observed, with many

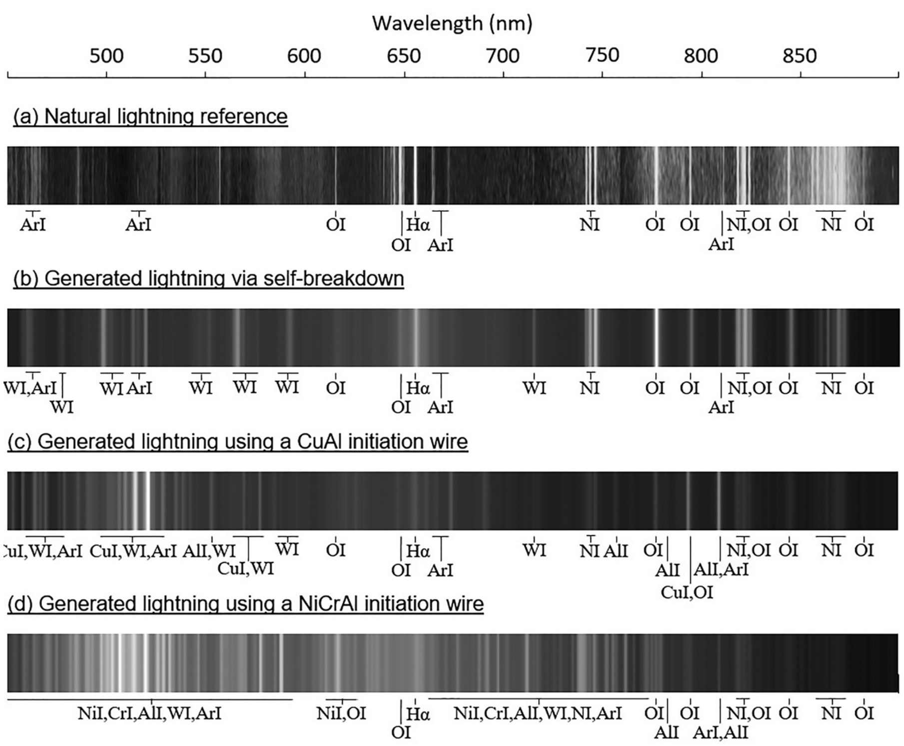

FIG. 4. A comparison of natural[2] and laboratory generated lightning emission spectra.

coincident and masking lines from the air and electrodes. Such a large number of lines added to the amount of light emitted, and the lightning arc appears somewhat brighter than the previously two generated lightning arcs. Although similarities do still exist between the experimental and natural lightning, it is clear that the use of the NiCrAl wire has flooded the spectrum.

The prominence of lines from both initiation wires can be explained by considering the ionization energies of their constituents: copper, aluminium, nickel, and chromium, which are all below 580 kJ/mol, and comparing these to the constituents of air; nitrogen, oxygen and argon which are all above 1,300 kJ/mol (with tungsten at 770 kJ/mol).[25] Hence, during the lightning experiments, there were more electron transactions within the initiation wires than the surrounding air resulting in a series of brighter lines. Atomic energy levels and electron transition probabilities for each element also play a part in the position and relative intensity of each line, with chromium having an atomic structure which resulted in numerous prominent lines throughout the observed wavelength range.

Overall, in terms of elemental interactions and emitted light, it can be seen that the generated lightning via self-breakdown is a much better representation of a natural lightning event than when an initiation wire is used. The results illustrate the suitability of the proposed spectrograph technique which has identified the importance of the method used to initiate generated lightning, and how this could affect its comparability to natural lightning events in terms of the amount and wavelength of light emitted. Notably, how some materials, whether electrode, initiation wire, or other components with which the lightning interacts, may introduce a large number of unwanted spectral lines or more light intensity than expected. Where emitted light or diagnostic methods reliant on emitted light are important, then great care must be taken to select appropriate materials to avoid masking effects. Alternatively, the results also illustrate how materials with which lightning interacts can be identified through spectral analysis, and this may play a role in the increasingly important area of material science and contribute towards the understanding of natural phenomena. An example includes recently reported spectral observations of ball lightning[26] indicating that it may be generated through lightning interactions with the surrounding soil. Future work may be able to verify this experimentally within a laboratory environment.

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