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SUSTAINABLE ENERGY

Spectroscopic Measurements of Light Emissions from High Current Arcs

Due to the destructive impact of lightning, and the risk of increasing strikes attributed to climate change on the natural and built environment, work has been carried out to study the temperature and light emitted by laboratory generated lightning using non-invasive light-based instrumentation, which will allow optimisation of lightning protection. Using spectroscopy, the optical emission spectrum of a 55 kA lightning arc with a copper fuse wire was obtained for study. The results showed the light radiated in the visible and infrared range, with strong copper emission lines seen, and determined a temperature of the arc of 8,531±577 K. This is in preparation for sub-nanosecond resolution data to be recorded using a new streak spectrograph to create temporal data of lightning arcs. A new laboratory experimental set up is being developed to explore further electromagnetic emissions in the infrared, ultraviolet and x-rays, to derive other useful information about lightning phenomena.

Keywords:
Lightning phenomena, engineering, physics, spectroscopy, temperature, atomic emission lines.

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M. Hills, P. Lugg-Widger, N. Peretto, A. Haddad, and D. Mitchard, ‘Spectroscopic Measurements of Light Emissions from High Current Arcs’ *Cardiff University Engineering Research Conference 2023*, Cardiff, UK, pp. 158-162.

doi.org/10.18573/conf1.aj

INTRODUCTION

Lightning is one of the most unpredictable and destructive phenomena in nature, which can cause critical damage to infrastructure, transportation and power networks, and lead to natural disasters such as uncontrolled wildfires. As global temperature increases due to climate change, it is estimated that the energy of lightning strikes will also increase, as well as its frequency by 5 – 6 % per degree Celsius [1-3]but the impact of global warming on lightning rates is poorly constrained. Here we propose that the lightning flash rate is proportional to the convective available potential energy (CAPE. There is a growing scientific interest in understanding the interactions and further characteristics of lightning. The temperature, energy, arc initiation and duration of lightning arcs are all important parameters to study and improve their quantification to allow optimised lightning protection [4]. However, lightning is difficult to study in nature, as well as when generated in a laboratory, particularly because it can damage or destroy most instrumentation and analysis techniques. Therefore, non-contact, non-invasive techniques are required to ensure the safety of measuring equipment.

In this study, a detailed high-resolution spectroscopy and imaging was carried out to demonstrate the ability to obtain characteristic elemental interactions and arc temperature from a laboratory generated lightning strike. This type of technique will form the basis of a new laboratory experimental facility dedicated to the development of light-based measurement techniques, from soft x-ray to infrared. This will then allow further studies to be conducted, which may contribute towards other research areas, such as combustion.

BACKGROUND

Blackbody radiation is the spectrum of Electromagnetic (EM) energy emitted by all objects, with an ideally opaque, non-reflective body emitting a perfect curve. This continuous spectrum can indicate many characteristics of objects such as the temperature and the power radiated. As a body begins to rise in temperature, the total emitted radiation rises as given by Planck's Law (Eq. 1):

$$L(\lambda, T) = \left(\frac{2hc^2}{\lambda^5}\right)\left(\frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}\right) \quad (1)$$

where L is the spectral radiance [W m^{-2} sr^{-1}], h is Planck's constant (6.63 x10^{-34} [J s]), c is the speed of light (3.00 x10^{8} [m s^{-1}]), λ is the emitted wavelength [m], k_B is the Boltzmann constant (1.4 x10^{-23} [J K^{-1}]) and T is the temperature [K].

As well as an increase in radiation emitted, the wavelength at which the intensity is at its peak decreases due to Wien's Law (Eq. 2):

$$\lambda_{max} = \frac{b}{T} \quad (2)$$

where λ_{max} is the peak emitted wavelength [m] and b is Wien's displacement constant (2.90 x10^{-3} [m K]).

An illustration of these laws is given in Fig. 1, where the spectral radiance in a lightning strike is several orders of magnitude higher than the radiance of a human. Also included are the radiation curves of the surface of the sun (≈ 5,500 K), and that of a large campfire or a Bunsen burner's flame (≈ 1,500 K). The area under these curves is proportional to the energy and, as such, indicates that the energy radiated by an object also increases as temperature rises.

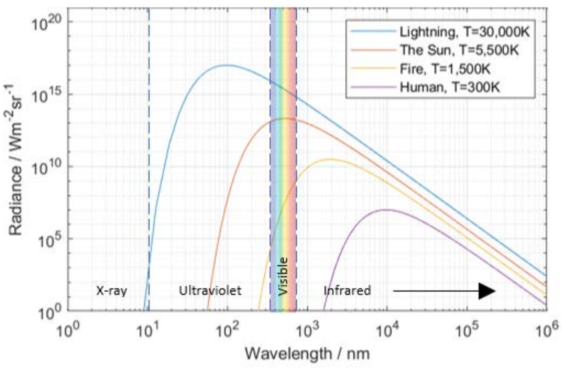

Fig. 1. The Blackbody Radiation Curves derived from the temperature of a lightning arc, the sun, a typical fire, and a human. Temperatures (T) are given in the legend.

With an average temperature of around 30,000 K, it can be seen that lightning primarily radiates in the ultraviolet range, unlike other objects. These low-wavelength electromagnetic waves are extremely high in energy but have not been studied in great detail. Studies of the blackbody radiation of lightning have primarily investigated the near-infrared (NIR) and visible wavelength of the EM spectrum.

Another characteristic phenomenon seen in the spectrum is atomic emission lines. When individual elements are excited by an energetic event, photons with certain wavelengths, specific to that element, are absorbed and re-emitted. By measuring the overall light emitted from an event, several elements can be identified with their respective emission lines. For example, if a spectrograph records a high intensity of photons with a wavelength of 777.4 nm, this can be identified as oxygen-I [5]. Many elements display a unique colour when heated due to having several prominent emission lines at a visible wavelength. Examples of this include copper burning blue-green with lines at 510.6, 515.3 and 521.8 nm to name a few, and sodium appearing yellow when energised due to prominent lines at 589.0 and 589.6 nm [6], which is why sodium street lamps glow yellow. One method of measuring the temperature using emission lines is the 'two lines method' [7-10]. When a plasma is in local thermodynamic equilibrium, the relative intensities of two spectral lines (of the same element) can be used to determine the temperature. Using two lines with different excited state energies, the temperature of an event can be found using Eq. 3 [9,10]:

$$T = \frac{E_2 - E_1}{k_B} \cdot \left[\ln\left(\frac{I_1\lambda_1 A_2 g_2}{I_2\lambda_2 A_1 g_1}\right)\right]^{-1} \quad (3)$$

where T is the temperature [K], E_i is the excited state energy of line i [J], λ_i is the wavelength of the line [nm], I_i is the intensity of the line, g_i is the statistical weight, A_i is the probability of transition [s^{-1}] and k_B is the Boltzmann constant (1.38 x10^{-23} [J K^{-1}]).

EXPERIMENTAL METHOD

To generate lightning with characteristics similar to those of natural lightning, a 100 µs, 55.5 kA D waveform was used in accordance with the EUROCAE ED84 standard and its SAE equivalent [11]. A graph showing this measured current waveform is given in Fig. 2.

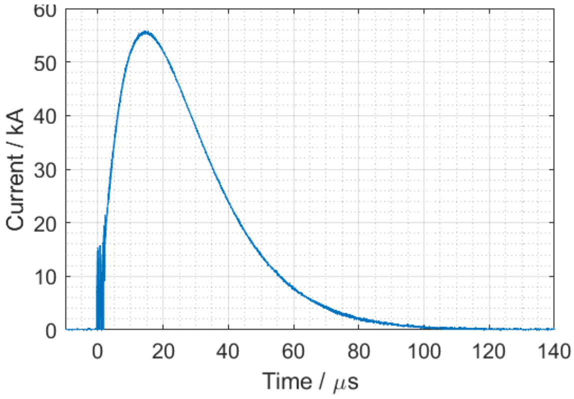

Fig 2. A 100 µs, 55.5 kA D lightning waveform arc.

A stainless steel rod electrode with a diameter of 15 mm was placed 45 mm away from a flat aluminium grounding plate, These selected materials allow for minimal damage during repeated impulse testing. As per the ED105 Standard [12], an insulating ball is threaded onto the electrode and a 0.1 mm diameter copper initiation wire is attached from the end of the electrode to the grounding plane, which helps to create a conductive path for the arc and then vaporises early during the impulse front. However, the thin fuse wire can also be used to obtain prominent emission lines providing useful information for temperature calculations. Fig. 3 shows the electrode arrangement as well the Czerny-Turner integrated spectrographic system used to record the spectrum, observing and integrating all light emitted during the 100 µs event. Light data is recorded from visible wavelengths at 390 nm to the infrared range at 950 nm. A subrange of 560 nm allows many atomic lines to be seen and a more accurate calibration to be performed before recording the data. A wavelength resolution of 0.55 nm is achieved using a diffraction grating of 150 lines/mm and a blaze of 300 nm. An optic fibre is used to collect the light emitted, with a collimator to prevent oversaturation. Using a slit size of 50 µm at the opening of the spectrograph, and an exposure time of 5 s, light is collected into the spectrograph and reflected using mirrors and a diffraction grating. It is then received by a CCD camera array of 1024 pixel bins.

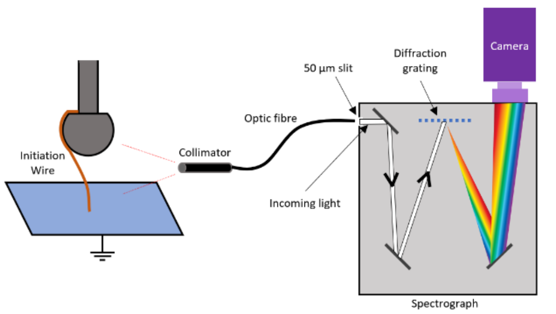

Fig 3. A schematic of the experiment set-up and the inner workings of the spectrograph. A stainless steel rod with an insulating ball was placed 45 mm away from the aluminium grounding plate, with a copper initiation wire connecting the two.

A mercury-argon light source was used to calibrate the system. To avoid any background noise, several spectra were taken when no event occurred, to subtract these values from the final results. This ensures all data analysed is from the event alone.

To capture the photographic image of the event, a full-frame DSLR was used with a shutter opening time of 6 s. Attached to the lens of the camera were two ND64 (neutral-density-6-stop) filters to reduce saturation in the image.

RESULTS AND DISCUSSION

A spectrum of a 55.5 kA lightning impulse was recorded and analysed to identify elemental emission lines. From this record, a temperature measurement was estimated.

Figure 4 shows a photographic image of the arc. The colours seen in the image already give an indication to the elements that will be seen in the spectrum. Copper vapour emits a blue-green colour due to prominent atomic emission lines in that section of the EM spectrum. The orange in the background is the vaporising wire, illuminated by the arc.

Fig 4. An image of a 55.5 kA lightning arc taken with a shutter opening time of 6 s.

Using an integrated spectrograph, Fig. 5 shows the total atomic emission obtained over the entire arc lifetime. Prior to studying the results, several post-data analyses were undertaken. A background spectrum was taken and subtracted from the final results, and other factors such as quantum efficiency and optic fibre attenuation (as well as anomalies such as cosmic rays) were taken into account. These peaks were then processed into an intensity plot. This allowed for clearer imaging of emission lines.

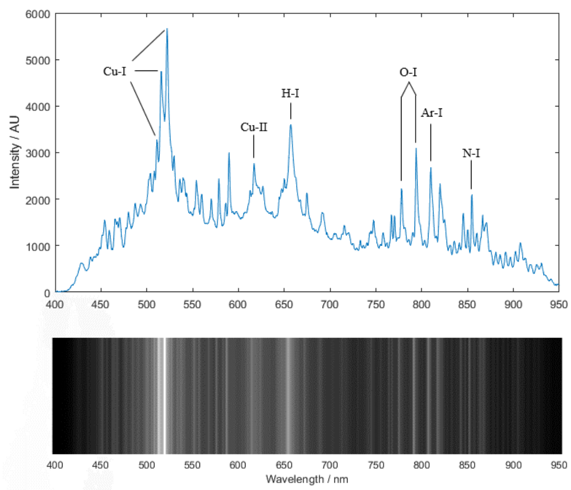

Fig 5. A spectrum and an intensity plot of the spectrum of a 55.5 kA lightning arc using a copper initiation wire.

By employing a coding script in MATLAB, the most prominent peaks in the spectrum were identified and recorded, with examples seen in Appendix A. Using a database of emission lines found in [5,13,14], prominent elements were then matched. These peaks may sometimes be broader than expected or may be different emission lines combined into one peak due to lack of resolution, especially when recording a wide wavelength range. To avoid misidentifying peaks, the three strongest copper-I peaks were used for temperature assessments. The wavelength of these peaks are in the blue-green section of the visible spectrum, hence the colour found in Fig. 4.

Examples of three prominent peaks of copper-I are found in Table 1. This includes the information required to calculate a temperature measurement of the arc.

Cu-I Peak	Wavelength [nm]	Energy [J]	Intensity [Counts]	g	A [s^{-1}]
1	Cu-I	2558	3273	4	0.2×10^{-9}
2	Cu-I	3274	4749	4	6.0×10^{-9}
3	Ar-I	2677	5673	6	7.5×10^{-9}

Table 1. The emission line information for three peaks of Cu-I [5].

Using the values shown in Table 1 in Eq. (3), two different temperature values were calculated. When comparing peaks 1 and 2, a temperature of 9108±273 K was calculated and when comparing peaks 1 and 3, a temperature of 7954±239 K was found. Errors are estimated to be around 3% of the temperature value. These temperature values have a considerable difference, but this is due to the temperature being an average, integrated, value across the entire arc length (100 µs) and so the intensity of emission lines varies slightly during that duration. Measurements were also taken under the assumption of local thermodynamic equilibrium, which is likely not the case over the entire arc period. Additional analysis can be carried out to obtain a more accurate average value by comparing further peaks, examining the emission lines of other elements within the same arc, and by measuring the spectrum emitted at time intervals, with smaller ranges allowing for more accurate results.

CONCLUSIONS AND FUTURE WORK

Using integrated spectrograph systems, temperature values have been calculated for lightning arcs, but these measurements have relatively large differences (around 1,200 K, which is approximately 15%). As such, more detailed work would need to be undertaken to reduce this margin of error by primarily using a greater resolution and different emission spectra for the analysis. To improve the experimental results, streak spectroscopy measurements will be undertaken. This offers advanced and faster time-resolved measurements which improves accuracy. Such streak camera-based spectroscopy will allow temporal temperature measurements to be calculated at any point during the arc's lifetime, and thus a detailed variation in temperature can be obtained.

A new experimental set up will be developed to allow new more accurate experiments in this field to be completed. As well as detailed temporal spectroscopy, this next laboratory setup will allow x-ray emissions of an event to be measured and further complement a schlieren imaging system. As lightning emits x-rays, this will give critical information to the blackbody radiation of such an event.

Acknowledgments
The authors gratefully acknowledge the financial support provided by the EPSRC DTC and NERC Project NE/X010848/1.

Conflicts of interest
The authors declare no conflict of interest.

Appendix A

Wavelength [nm]	Estimated Element [5]	Intensity [Counts]
503.7	Cu-I	2558
510.6	Cu-I	3274
515.4	Cu-I	4749
521.5	Cu-I	5673
529.4	Cu-I	2928
589.5	Ar-I	3005
617.0	Cu-II	2776
656.3	H-I	3604
793.8	O-I	3102
809.9	Ar-I	2677

Table 2. The intensity and wavelengths of prominent peaks found in a spectrum of a 55 kV copper-led lightning arc.

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Cynhadledd Ymchwil Peirianneg Caerdydd
Cardiff Engineering Research Conference

E. Spezi and M. Bray (eds.) 2024. *Proceedings of the Cardiff University Engineering Research Conference 2023.* Cardiff: Cardiff University Press.
doi.org/10.18573/conf1

Cardiff University Engineering Research Conference 2023 was organised by the School of Engineering and held from 12 to 14 July 2023 at Cardiff University.

The work presented in these proceedings has been peer reviewed and approved by the conference organisers and associated scientific committee to ensure high academic standards have been met.

Cardiff University Press | Gwasg Prifysgol Caerdydd

First published 2024

Cardiff University Press
Cardiff University, PO Box 430
1st Floor, 30-36 Newport Road
Cardiff CF24 0DE

cardiffuniversitypress.org

Editorial design and layout by
Academic Visual Communication

ISBN: 978-1-9116-5349-3 (PDF)