Atomic oxygen photometric plasma diagnostic of lightning

Caitano L. da Silva[(*)1], J. Wemhoner[1], A. F. R. Leal[1], J. G. Pantuso[1]
(Times 12, normal, centred)

[1] *Department of Physics & Langmuir Lab, New Mexico Tech, Socorro, NM, USA*
[(*)] caitano.dasilva@nmt.edu

For thousands of years lightning has been one of the most astonishing natural phenomena, being both frightening and fascinating. Lightning is an important process in the atmospheric energy budget, contributing to the global electric circuit and to the production of nitrogen oxide in the troposphere. Concurrently, lightning discharges are known to be a major source of damages for a wide range of systems, amounting up to $5 billion/year economic losses in the United States (alone), mostly in the air flight and electric power distribution industries. In the United States dry southwest, lightning is a major cause of forest fires every year. For many years, the primary, if not the only, kind of widespread lightning diagnostics has been radio-frequency remote sensing of lightning peak currents. Lightning peak currents serve as proxy for the potential damage a strike may cause, including producing the effects listed in the previous paragraph. However, a simple argument can be made that the plasma temperature is substantially more informative about the potential deleterious effects of lightning flashes. Lightning return strokes establish a near-equilibrium plasma at peak temperatures of $\sim$30–40 kK. This value is 5–7 times the surface temperature of the Sun, several times higher than the melting temperatures of metals used in practical applications, and tens of times higher than the value required for ignition of a forest fire.

In this work, we present a new methodology to probe lightning temperatures from its optical signals. More specifically, we perform narrowband (1 nm) photometric measurements of lightning around key atomic oxygen lines in the near-infrared: 777, 844, and 926 nm. In thermal equilibrium, the light intensity emitted by an electronic transition is proportional to the overall plasma temperature. Thus, the ratio of two line emissions (e.g., 844/777) uniquely defines the temperature [14, 2]. If the plasma is not in equilibrium, the inferred temperature effectively is the temperature of the species probed (oxygen atoms in this case). Nonetheless, in practice, this value should be a good predictor of the overall temperature of neutral species in the hot plasma. Narrowband photometry is a relatively-inexpensive approach to probe the spectral properties of lightning optical emissions [10, 15]. Additionally, the setup introduced here has great potential to provide fully-automated, routine measurements of the lightning plasma temperature.

In the Summer of 2023, we performed measurements of lightning, using multi-band optical and radio sensors, at New Mexico Tech's Langmuir Laboratory for Atmospheric Research — a mountain-top facility in the southwest of the United States dedicated to lightning and thunderstorm research. Instrumentation used included: the atomic oxygen photometer array, fast and slow electric field change antennas, and a 3D VHF lightning mapping array [11]. Supporting data sets included lightning location provided: by the Earth Networks Total Lightning Detection Network (ENTLN), and by the Geostationary Lightning Mapper (GLM) on board of NOAA's Geostationary Operational Environmental Satellites (GOES) [7]. In this presentation, we report the inferred temperature of lightning and how it relates to its spatial and electromagnetic properties. We ascertain what factors determine temperature, such as peak current, occurrence context, height above ground of sources, discharge polarity, etc. We also compare the photometric measurements to simulation [5, 13] and determine that the field-of-view-integrated photometric measurements predict a temperature which corresponds precisely to the optical power-weighted-average temperature. This means that the measured peak temperature is not exactly identical to the actual peak temperature in the plasma. It approaches that value, but because of the average across the field of view, it falls a couple thousands of degrees Kelvin shorter. If time permits, we shall also take this opportunity to provide a brief overview of the atmospheric electricity research taking place at Langmuir Lab, including: rocket-triggered lightning [6], high-resolution lightning mapping [8], lightning initiation [1, 12], sprite observations [3], and runaway electron acceleration [9, 4].

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