Novel Observations in Lightning Spectroscopy

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ABSTRACT: In the mid 1960s, Leon Salanave, Martin Uman and Richard Orville laid the foundation for lightning spectroscopy. They were the first to acquire time resolved return stroke spectra and the first to use spectroscopy as a diagnostic technique to characterize physical properties of the lightning channel [e.g., *Salanave*, 1961; *Uman*, 1966; *Orville*, 1968a]. Now, almost 50 years later, technology, including CMOS and CCD high speed cameras, volumephase holographic (VPH) gratings, and triggered lightning, has progressed to the point at which studies in lightning spectroscopy are needed to verify and extend past measurements. New spectral lines have been discovered in the lightning spectrum as a result of the new studies, mainly doubly ionized nitrogen lines which had not been observed in the past. Modern techniques use CMOS and CCD cameras with frame rates up to 1Mfps and exposure times down to 0.5 microseconds. The high frame rate paired with the camera memory enables a view into the quick high temperature heating period within the first few microseconds of the return stroke as well as a detailed look at the cooling period which can last for milliseconds. These cameras also record the spectra digitally and discretely, hence the data can be summed to achieve different exposure times revealing long lasting low emission lines especially those of neutral oxygen which tend to be of lower intensity. Specific processes analyzed include stepped leaders, dart-stepped leaders, and stroke processes. Spectra of the stroke processes, M components and continuing currents, are comprised of neutral atmospheric and copper lines which demonstrate the long duration of the channel milliseconds after the initial stages. These spectra indicate long lasting low temperatures extending to the point where NOx reactions can occur. The spectra during each of these processes provides insight into the physical processes that are occurring.

INTRODUCTION

Among others, lightning spectroscopy was studied extensively in the 1960s by Richard Orville, Leon Salanave, and Martin Uman. One of the first notable publications about lightning spectroscopy was Salanave's article in Science in 1961 [*Salanave*, 1961]. This article was an overview of lightning research up to 1961 from the observations of astronomers in 1901 to Salanave's own spectra. Salanave discussed significant lines that show up in lightning spectra such as the hydrogen lines, which are due to the disassociation of water vapor in the discharge and the most predominant features NI (neutral nitrogen), NII (singly ionized nitrogen), OI (neutral oxygen), and OII (singly ionized oxygen). Two years later Melvin Prueitt published "The Excitation Temperature of Lightning," which detailed the method for deriving the electron temperature from the lightning spectrum and the assumptions required to perform the calculations [*Prueitt*, 1963]. Richard Orville, who was the first to map out the spectrum of lightning in detail, published a three part paper on high speed time resolved spectroscopy in 1968 [e.g., *Orville*, 1968a,b,c]. This set of articles was the peak of the lightning spectroscopy research.

The technology of the past had a few disadvantages: the over/under exposure of images, time consuming photodensiometer tracings, non-linear response of film, and film speed. Technological advances which have improved upon previous studies include implementing CCD and CMOS imaging which provides a higher degree of sensitivity to light, higher speed operation and a more linear response to light, data processing, and the ease and portability of the spectrograph system. Also, access to triggered lightning at the International Center for Lightning Research and Testing (ICLRT) located in Camp Blanding, Florida provides the opportunity to acquire a large number of spectra with high temporal and spatial resolution.

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INSTRUMENTATION

The main camera used in this study was the Phantom v710. The Phantom v710 is a CMOS camera with an array of 1280x800 20 μm pixels. The v710 is a monochrome camera with a 12 bit dynamic range. To achieve higher frame rates we reduce the resolution to 1040 x 8, which allows for a frame rate of 673k frames per second (fps); however, this limits the vertical field of view of the channel. The exposure time is set for $0.5 - 1$ μs. The camera has a rolling memory which allows for the trigger position to be anywhere within a one second time period before or after the return stroke which triggers the on-board image based auto-trigger.

Designing a spectrometer can be complicated, however due to the physical nature of lightning channel, the advancement of spectroscopy technology, and the use of transmission gratings this has been made easier. Since the lightning channel is a vertically oriented line emitter, it essentially acts as its own slit. Therefore it is unnecessary to build a spectrometer with a physical slit. We have also eliminated complicated lens systems while maintaining high spectral resolution by using a grism, which is a combination of a diffraction grating and a prism. The prism redirects the light of the first order spectrum from the diffraction grating causing it to go straight through to the device. Taking this into consideration, a set of volume-phase holographic (VPH) grisms were commissioned. The diffraction grating inside a VPH grism is an alternating series of indices of refractions rather than physical gratings. This improves spectral quality due to more light passing through the system as well as less light scattered due to the physical barriers present in traditional grating systems. Although at present we have three of these grisms, one designed for the lower visible wavelengths $3800 - 6000$ Å with a $2 - 3$ Å resolution and two designed for 6563 Å(Hα) and 7774 Å (OI triplet) with a 0.25 Å resolution, the information presented will primarily come from the first grism. Also note since we are using slitless spectroscopy, the wavelength range of the acquired spectra will depend on the orientation of the lightning channel with respect to the camera. To this end we have been able to study not only the region from $3800 - 6000$ Å, but wavelength ranges up to 9500 Å as well.

THEORY

In order to derive temperature measurements from the channel it is assumed the channel is in local thermodynamic equilibrium (LTE) as well as optically thin. These two criteria have been discussed in detail by Uman and Orville in particular [e.g., *Uman*, 1966; *Orville*, 1968b; *Uman and Orville*, 1965]. We will assume these to be true. If LTE does not exist, the temperature measurements will be an electron temperature rather than a thermodynamic temperature. Although it must be said that LTE is really only in question during the first few microseconds from which the hot temperatures of the channel are derived. If we take these assumptions as true, it can easily be shown that the temperature can be written as the ratio of intensities of two lines of the same atom at the same ionization stage,

$$T = \frac{\epsilon_m - \epsilon_n}{k \ln \left(I_{nr} g_m A_{mp} \nu_{mp} / I_{mp} g_n A_{nr} \nu_{nr} \right)}. \tag{1}$$

In equation (1), m and n represent the different states of the higher energy level, p and r represent the lower energy states of the transition, I is integrated intensity of the line, ν frequency of the line, g is the statistical weight of the energy level, ϵ is the energy of the state, k is the Boltzmann constant, and A is the Einstein emission coefficient. Hence, temperature is just a function of the ratio of these two lines, constants, and atomic information taken from the NIST (National Institute of Standards and Technology) database.

LIGHTNING SPECTRA

We divide the lightning spectrum into two main portions, the hot spectrum and the cooling spectrum. During the hot portion, which lasts from the onset of the return stroke until about 20μs, singly ionized and
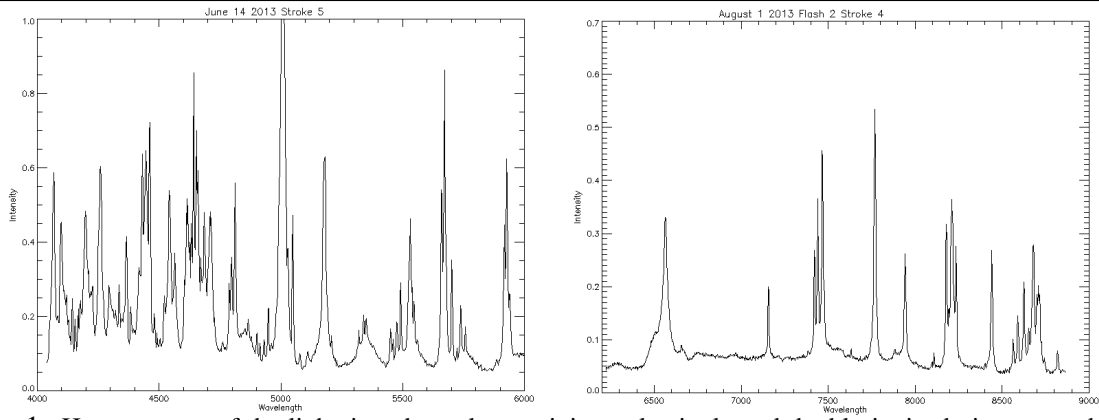
Figure 1: Hot spectrum of the lightning channel, containing only singly and doubly ionized nitrogen and oxygen, within a few microseconds after the return stroke (left). Spectrum to the cooling period, containing the neutral atoms of hydrogen, oxygen, and nitrogen, tens of microseconds after the onset of the return stroke (right).

doubly ionized lines dominate the spectrum. Typical peak temperatures during the first frame are in the upper 30000 K to low 40000 K range. The doubly ionized lines are only present for the first frame of the spectra and therefore peak during this $1.5\mu s$ period. The singly ionized lines peak next, and then die out during the next tens of microseconds. All the ionized lines die out during this $20\mu s$ period, as does the temperature fall off just as rapidly. Once the ionized lines die out, this begins the cooling period of the spectrum. Temperatures at this point are still around 20000 K. As soon as all the ionized lines have died out the neutral lines peak. During this cool period which can last for a few milliseconds or more, the neutral lines die out much more slowly than their ionized counterparts. On the left in Figure 1 is an example of a hot spectrum.

All of the lines in this spectra are either doubly or singly ionized lines. On the right in Figure 1 is an example of a "cool" spectrum, where all of the emissions represent neutral atoms. By combining all of this information, a detailed picture of the evolution of the atomic constituents within channel is obtained. The peak luminosity of the atomic constituents is as follows: initial peak of doubly ionized lines in the first μs, followed by singly ionized in the next $3\mu s$, then the neutral atoms around $20\mu s$ later, and finally by Hα within a few microseconds following the neutrals.

The temperature can be derived during hot portion of the return stroke, but it can also be determined as long as certain lines are above the measurement threshold. Typically at least one of the lines for measuring the cool temperature die out within a couple hundred microseconds, however if there is a continuing current
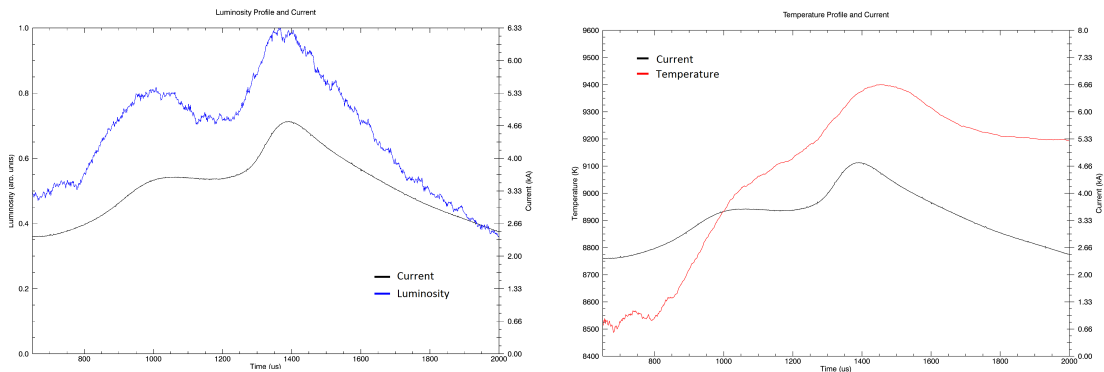

Figure 2: Luminosity (left) and temperature (right) profiles with current measurements during a continuing current increase.

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that is strong enough these lines will re-emerge. Such is the case in Figure 2. In Figure 2 the luminosity and current are shown together on the left. Notice the small changes can be seen in both. Now if we determine the temperature as can be seen on the right in Figure 2, the effect is less noticeable however is still there. Also notice that these temperatures around 9000 K, are occurring when the current is still only 4.6kA. The implication here is that the temperature of the channel remains elevated for milliseconds. And the profile down in the temperatures for molecular recombinations, around 5000 K, will last for similar times or longer

Other low intensity processes such as the stepped leaders and dart-stepped leaders have also been captured. Both leader spectra begin with an increase of the singly ionized lines which transition into neutral lines. The singly ionized lines pulse as the neutral lines grow throughout the lifetime of the leader. This pulsing of the ionized lines is due to the growth of the leader. At each step the channel is reilluminated from the tip backwards, reionizing neutral atoms along the channel up until the moment of the return stroke. Significant singly ionized emissions are present when the channel is about 25000 K. The stepped and dart-stepped leader must include hot processes at least in the leader tip and several meters up the channel where it is re-illuminated.

CONCLUSIONS

Typical spectra encompassing both the hot and cold portions of the spectral profile are presented. Relative populations during the heating and cooling periods follow the path expected for a hot emitter at or exceeding 40000 K which decreases rapidly to a monotonically decreasing temperature profile. Also demonstrated was temperature measurements for lower light emissions such as those during an M-component. Spectral profiles of both stepped and dart-stepped leaders with continuous neutral and pulsing singly ionized emissions are explained. The spectra of these processes demonstrate how hot leaders are.

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