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Improvements to a High Spectral Resolution, Radiation-Hydrodynamics Model of a Lightning Return Stroke and Comparison with Measured Spectra

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Motivation

The ability to identify and characterize lightning discharges from space is an area of significant interest for both geophysics and remote sensing. By developing a high-resolution spectral model for lightning, we can calculate how key features of the spectrum vary with physical parameters like the energy of the strike, air humidity, and ambient air density. Forward model calculations will allow us to predict sensor response to lightning, and inverse model runs will allow us to retrieve physical parameters from observations.

In order to evaluate the realism of our model, we compare our simulated spectra with measurements taken by Smith[1] at Sandia National Labs.

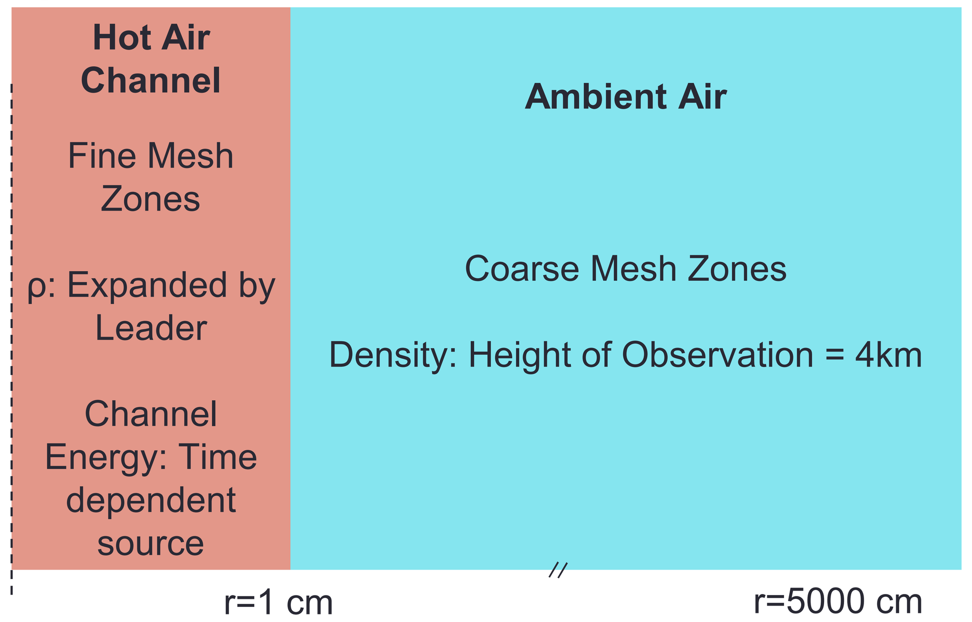
Model Components

Our lightning model is a gas-dynamics model closely related to [3], includes radiative heat transfer but does not include resistive heating or a circuit model. It uses 3 physics packages:

Radiative Heat Transfer: The radiation model uses a multi-group approximation in photon energy and a finite-difference scheme in space. This scheme is based on a modified two-stream approximation and derived similarly to [2].

Hydrodynamics: The hydrodynamics model is a Lagrangian finite difference method, which uses the von-Neumann-Richtmyer artificial viscosity scheme for treating shock fronts.

Spectrum Emission: Similar to the radiative transfer model with a 7000 group high-resolution atomic line opacity table built with PrismSPECT and PROPACEOS [4,5] .



Inferring Plasma Conditions from Measured Spectra

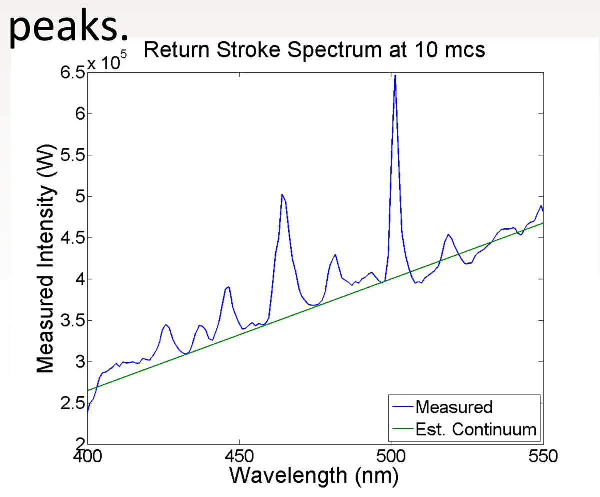
We compute the plasma temperature of the lightning channel from measured spectra by optimizing a theoretical spectral model against measured data.

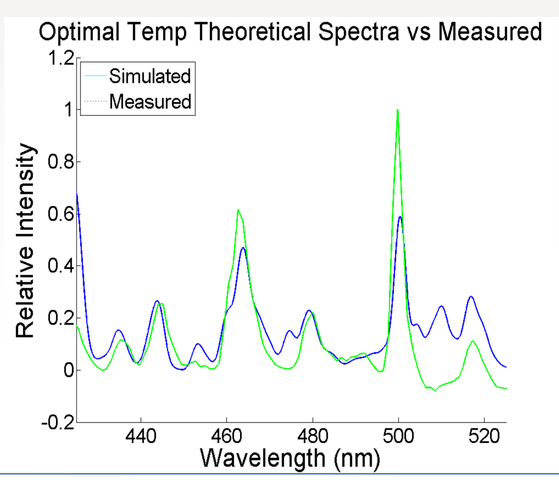
Theoretical Model

We develop a simplified routine [6] that uses atomic transition information from NIST to compute a theoretical air plasma spectrum at a given temperature. This routine incorporates Doppler and instrument broadening and applies these intensities to a psuedo-Voight profile.

Optimization Method

1. Use a straight-line approximation to remove continuum from the spectrum.
2. Use constrained optimization to adjust temperature and broadening parameters in the spectrum model until a "best fit" is found.
3. The best fit is defined with a cross-correlation between theoretical spectrum and measured peaks.





Consideration of Leader Stroke

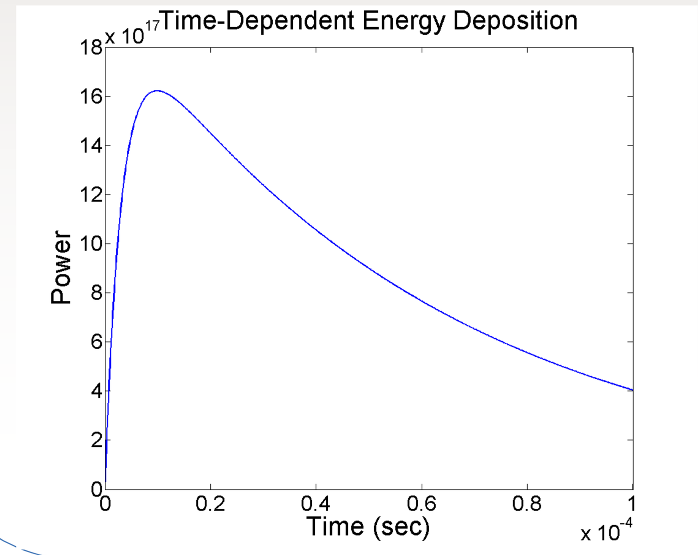
The leader stroke plays an integral role in the evolution of the gas-dynamics of the return stroke because it not only changes the conductivity of the channel, but it also pre-heats and pre-expands the air. Our calculations show that a pre-expanded channel is necessary in order to make the channel optically thin.

To account for this, we initialize our model by assuming the conditions described in [7]: that the channel has been heated to 10,000 K and expanded, reaching pressure equilibrium with the surrounding air. This reduces the initial density of the lightning channel by roughly a factor of 25.

Lightning Energy Deposition

The energy from a lightning return stroke isn't deposited instantaneously into the channel or the surrounding air. Rather, there is a continuous energy deposition as the electrical current varies over time. In order to simulate this, we incorporate a time-dependent energy source into the radiation-hydrodynamics equations, which simulates this power build-up. This equation takes the form:

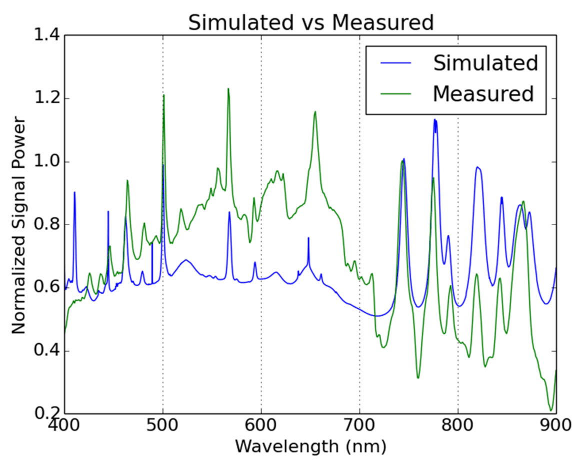
$$P = P_0\left(e^{-\alpha t} - e^{-\beta t}\right)$$

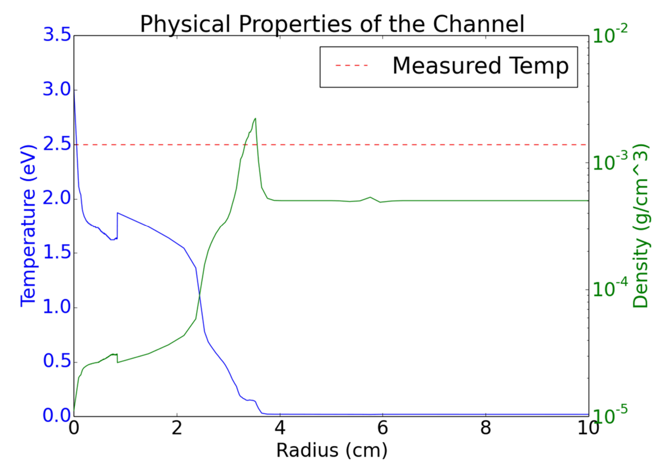


Simulating Lightning Spectra

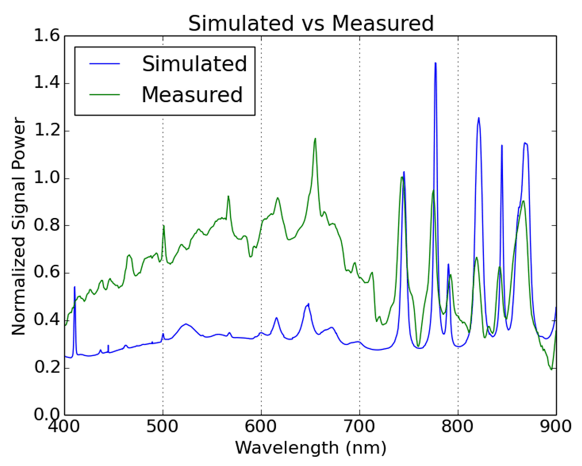
We use our radiation-hydrodynamic model to simulate high-resolution lightning spectra and compare them with measurements made by Sandia National Laboratory. In this example, we assume the channel has been pre-expanded by a factor of 25 to a density of 2e-5 g/cm^3. The external energy deposition reaches a peak at 10 μsec and decays exponentially.

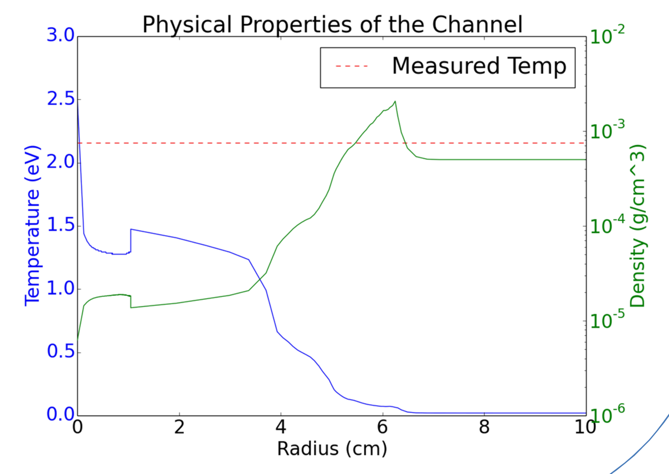
At 10 μsec, our simulation includes many of the same spectral lines from both ionized (447, 463, 480, 500, 568 nm) and neutral (746, 777, 844, 862 nm) nitrogen and oxygen; though our continuum is somewhat depressed. Our model's temperature profile is roughly 25% lower than our estimate of temperature from measured line ratio amplitudes. Increasing the model's channel temperature results in less satisfying agreement with the measured spectra.





At 30 μsec, our ionized spectrum is much less intense compared with the neutral spectrum, which is similar to the measured data; however, our continuum is much less than the measured. Again, our temperature profile is approximately 25% less than our estimation for the measured temperature.





Summary

We are developing a high-resolution model for simulating lightning spectra using atomic opacity tables with Angstrom-level resolution. This model assumes an air-channel pre-expanded by a leader stroke with continuous heating that mimics lightning current evolution. We compare our model spectra and temperature profile with similarly high-resolution measurements taken at Sandia National Laboratory, and our simulated spectra show similar features as it evolves in time to the measured data.

References

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NNSA National Nuclear Security Administration

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