Comparison of Modeled and Measured High-Resolution Optical Spectra from Lightning

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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 examine the behavior of our model, we compare our simulated spectra with measurements taken by Orville. [1]. We also show high-resolution digital measurements that we've made that will be useful for model validation.

Model Components

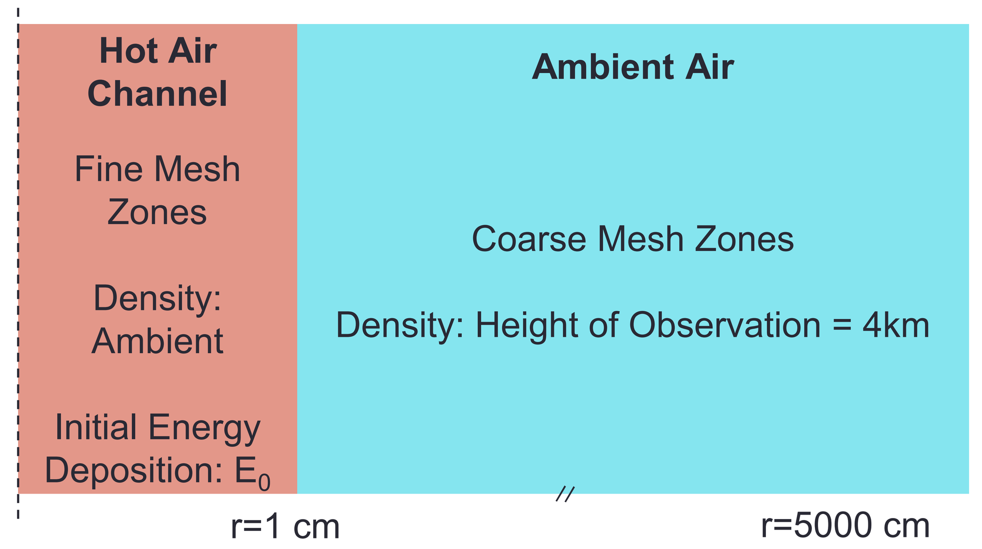
Our lightning model is a gas-dynamics model closely related to [3], which excludes EM but includes radiative heat transfer. It uses 3 physics packages:

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: This includes a radiation transport model with high-resolution atomic line opacities.

The model is initialized as:



High-Resolution Opacities

To compute the fine-structure atomic line opacities, we use two tools: PrismSPECT and PROPACEOS. [4,5] These tools use an extensive atomic transition database to compute opacities for free atoms at various levels of ionization. It includes an atomic model builder which allows the user to specify the amount of transition detail to incorporate for each ionization state, from thousands of transitions for a fully detailed state to 1 line for a state one does not wish to model. Contributions from molecular opacities are *not included* in the spectral model at this time.

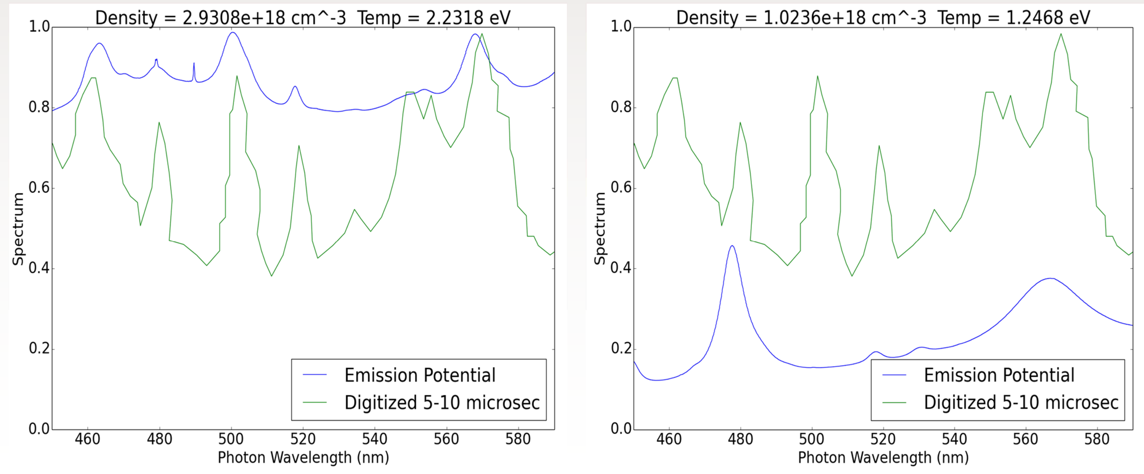
For this table, we consider a standard air composition with 4% H_2O. We build the table using 75 temperature points ranging from 0.1 -12 eV, 50 density points ranging from 1e16 – 3e20 ions/cm^3, and 4000 photon energy bins covering the 400-700 nm wavelength range. Thus, our opacity tables resolve the photon wavelength range of interest to less .than 1 Angstrom.

Evaluating "Emission Potential"

In order to evaluate our high-resolution opacity tables, we estimate their potential to generate an emission structure and compare with measured data. We consider the temperature and density profiles generated in our test problems, and taking the optimal temperature and density in that range, we compute an "emission potential" defined as:

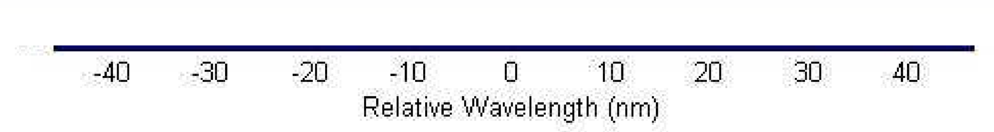
$$EP(\lambda) = 1 - e^{-\mu(\lambda)\Delta s}$$

where Δr is a characteristic thickness of emission. We compare the results with digitized measurements from [1] and find that some of the features are produced.



High-Resolution Measurements

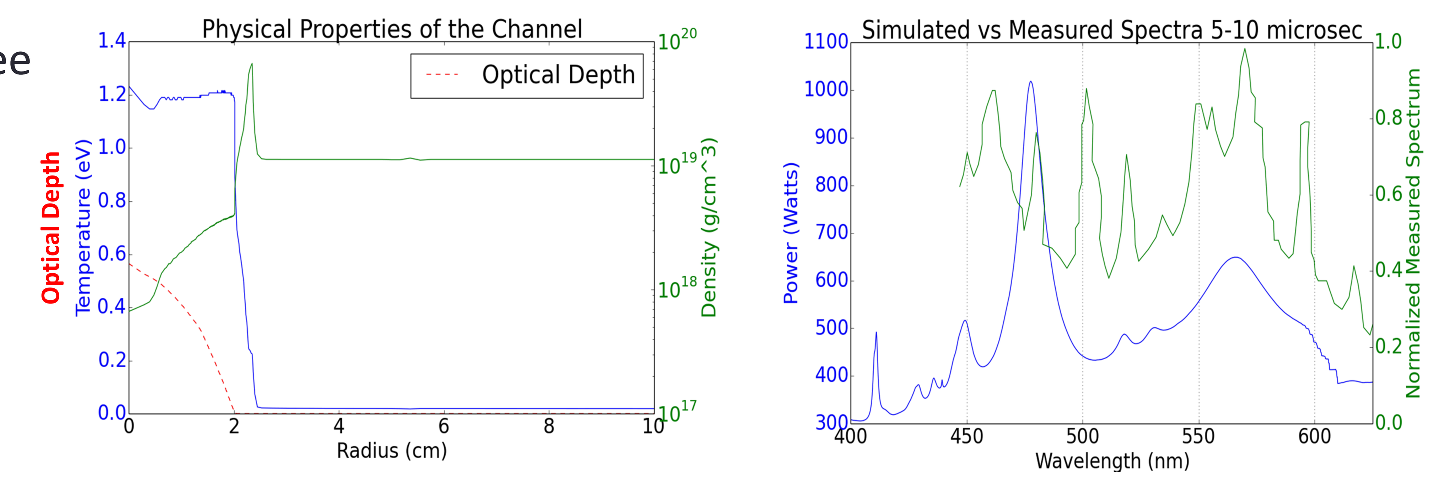
In addition to examining historical data published by Orville [1], we collected new data over the summer of 2014 using a high speed, slit-less spectrometer. This spectrometer consisted of a transmission diffraction grating placed in front of a standard Canon camera lens. The entire assembly was mounted to a Phantom v1210 high speed camera produced by Vision Research. The figure below shows lightning spectra collected at a rate of 400,000 frames per second, with a spectral sampling interval of 0.23 nm per pixel.



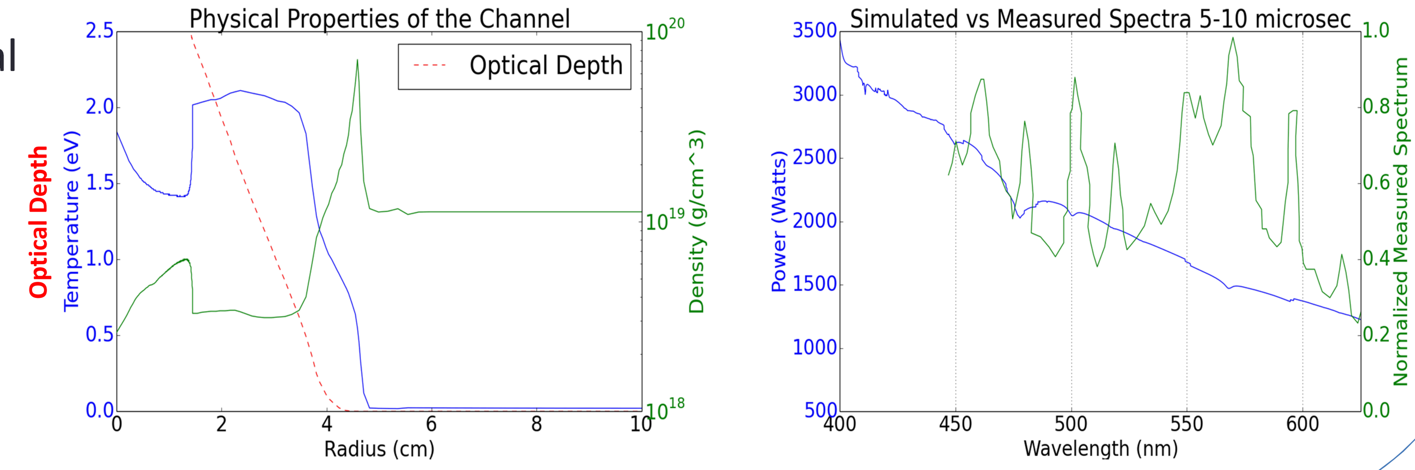
Simulating Lightning Spectra

We use our model with opacities generated by PrismSPECT and PROPACEOS to simulate high-resolution lightning spectra and compare them with digitized measurements from [1]. Here, we consider two example strikes with initial energy depositions of 200 J/cm and 2 kJ/cm into the lightning channel. Each of these cases uses a density of 5.41e-4 g/cm^3, which corresponds to an altitude of approximately 8 km, and has an initial channel radius of 1 cm.

In the 200 J/cm case (as suggested in [6]), we see that one optical depth for the 480 nm line encompasses the entire channel at 5 µs. Furthermore, while the overall shape and some of the emission lines are the same, some prominent lines are missing, e.g. the 468 nm and the 500 nm Nitrogen lines.



In the 2 kJ/cm case, the channel is several optical depths thick at 480 nm and thick at all wavelengths. The spectrum is a black body tail with absorption features at 455, 480, 500 and 570 nm. The measured spectrum on the other hand is dominated by line emission.



Summary

We are developing a high-resolution model for simulating lightning spectra. We have generated free-atom opacity tables with Angstrom level resolution, and our emission potential analysis shows that these opacities could yield an emission structure similar to that of previously measured data at certain temperatures and densities. We have also taken high-resolution measurements which will be useful for model validation. Currently, our simulated spectra do not match previous measurements, which suggests the physics included in this model is insufficient and should be expanded.

References

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