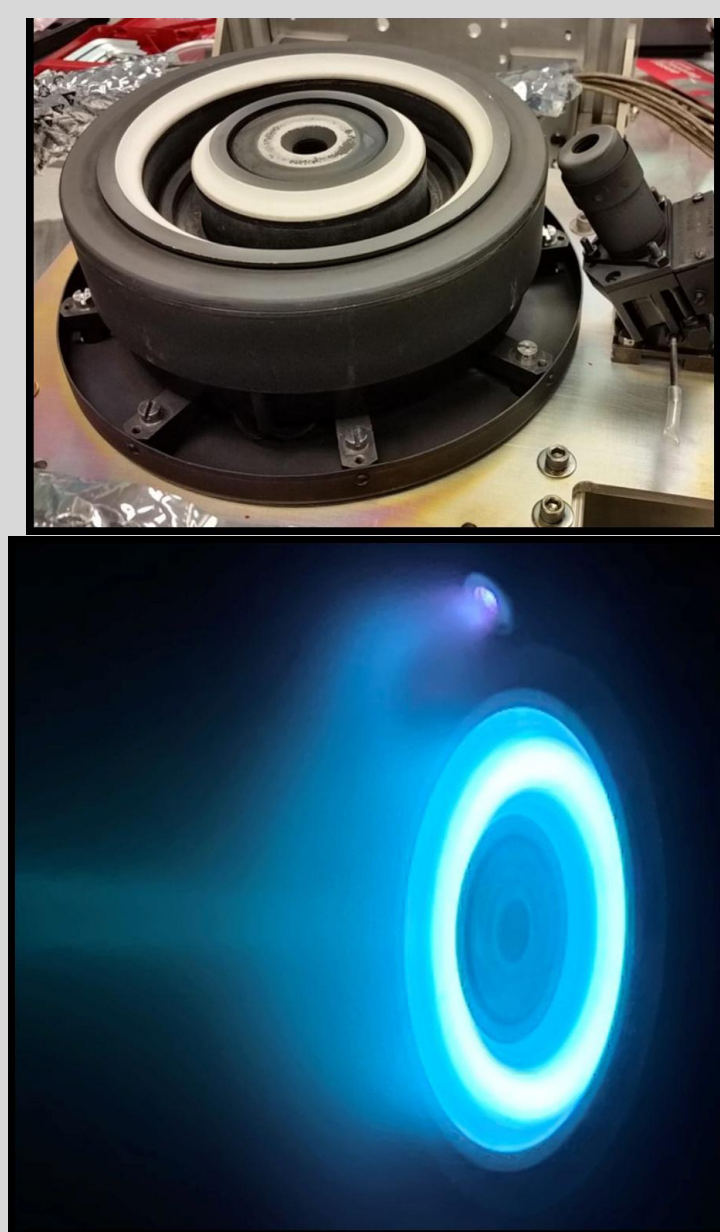


Abstract

Argon is increasingly used as the working gas in plasma electric propulsion systems for spacecraft, such as Hall thrusters. Non-invasive measurements of this kind of argon plasma are important in understanding plasma conditions and ramifications for thruster performance, and they are essential since direct probe measurements of a thruster plasma are impractical due to disruption of plasma conditions and overheating of the probe. Optical emission spectroscopy (OES) is one such non-perturbing diagnostic approach. To yield measurements of electron temperature and density it requires an accompanying collisional-radiative (CR) model of atomic processes. The CR model itself must be validated using direct Langmuir probe measurements of similar plasma conditions that are amenable to probe insertion. A new CR model has been developed for thruster-relevant argon plasma conditions based on the existing framework developed at NASA's Jet Propulsion Laboratory for xenon. Using new upgrades to an existing plasma production setup at the University of Alaska Anchorage, argon discharge data can now be taken over an expanded range of parameters, which will allow for more effective validation of the CR model. An ultraviolet-visible spectrometer (200-800 nm) is used to record argon emission spectra during radio frequency (RF) discharges and during afterglow. The RF discharges are combined with and compared to anode layer ion source DC discharges, and observed differences in OES measurements are analyzed. The OES spectrum coincide with physical Langmuir probe measurements, which facilitates the CR model development. A magnetic coil set is also employed to influence plasma conditions and yield a broader set of measurement parameters.

Background

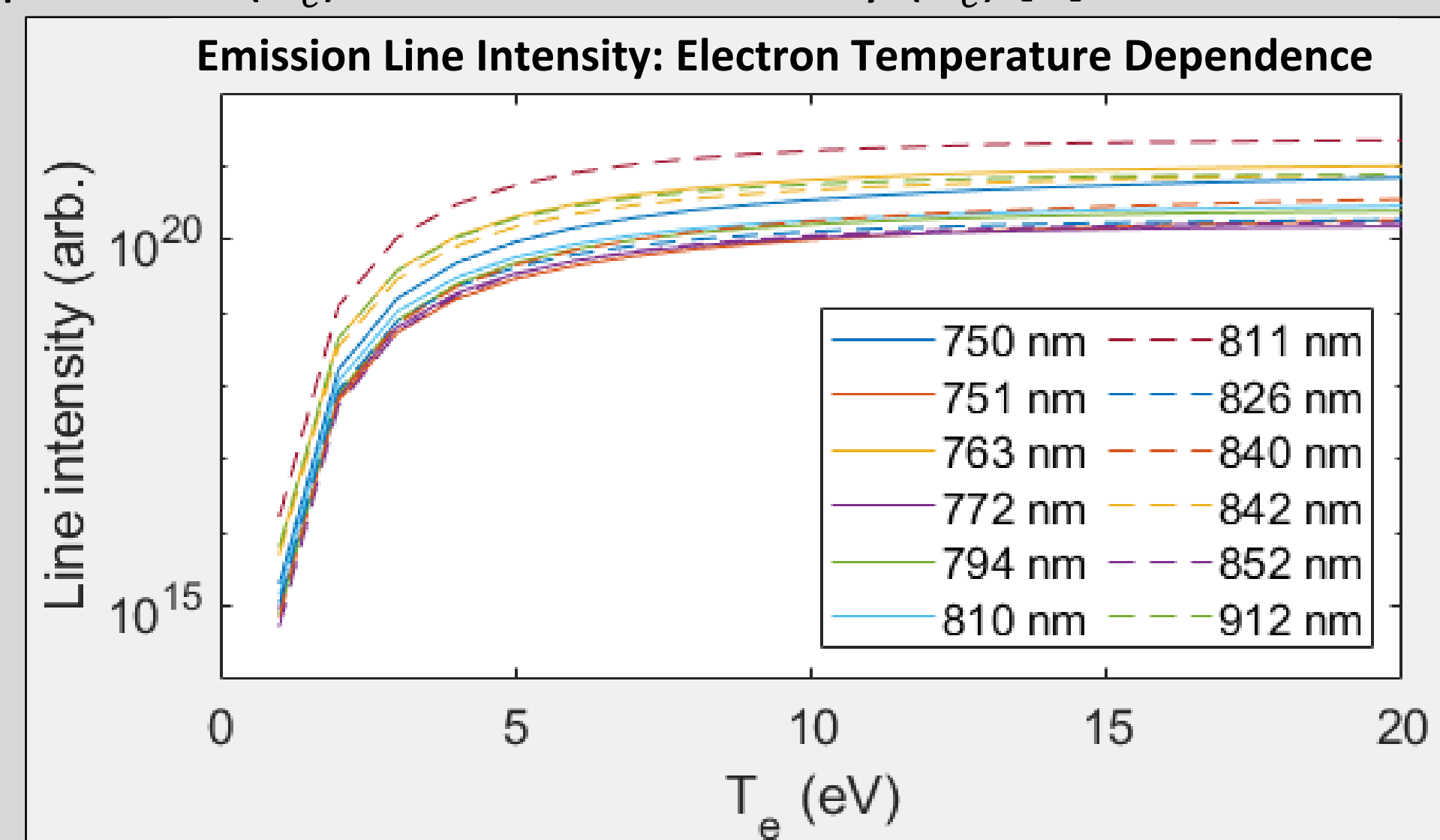
Electric propulsion (EP) thrusters are an alternative to traditional chemical rockets that achieve a comparatively higher specific impulse (1000 – 4200 s for state-of-the-art electric propulsion thrusters running on xenon [1, 4]) due to their very high exhaust velocities. Specific impulse is how to measure fuel efficiency of a thruster. This provides valuable benefits for planetary science missions including higher payload mass, launch window flexibility, elimination of critical events such as orbit insertion, and shorter flight times [1].



Optical Emission Spectroscopy

Light emitted from plasma discharges arises from spontaneous transitions of the electrons from a higher energy level to some lower energy level, emitting that energy in the form of a photon. That photon's wavelength is based on the energy difference between the states where the transition occurred. A spectrometer can take all the light emitted along a line of sight and split it into distinct wavelengths. The different wavelengths will have different intensities depending on how common the transition that causes that wavelength is. The rates at which these transitions happen is dependent on the electron properties of the plasma itself, particularly the electron temperature (T_e) and electron density (n_e) [6].

Analysis of OES data to find these electron parameters is accomplished with a CR model, which uses values for excitation cross sections and spontaneous transition rates, gathered from either NIST databases or literature to calculate emission line intensities as a function of T_e and n_e .



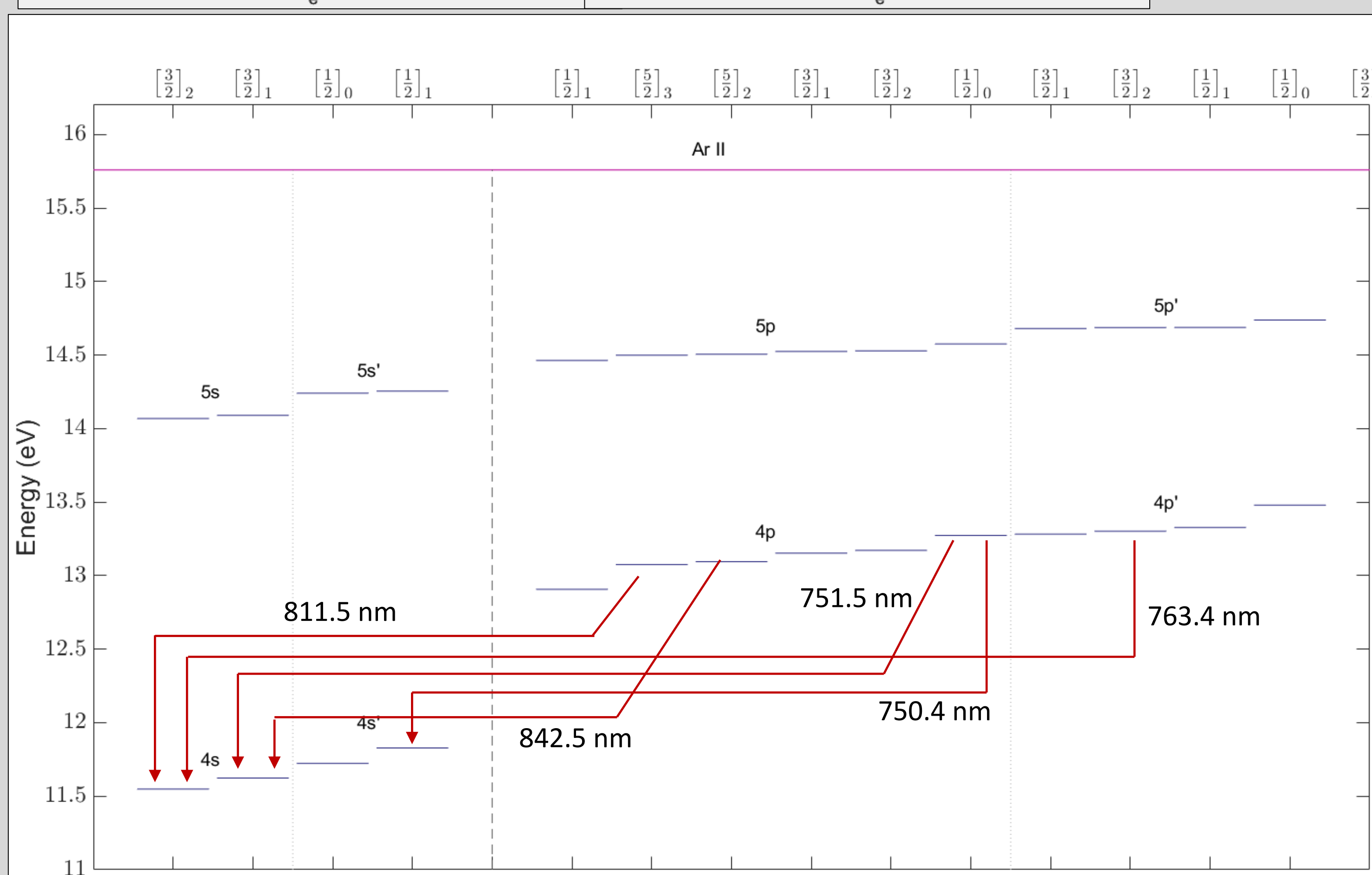
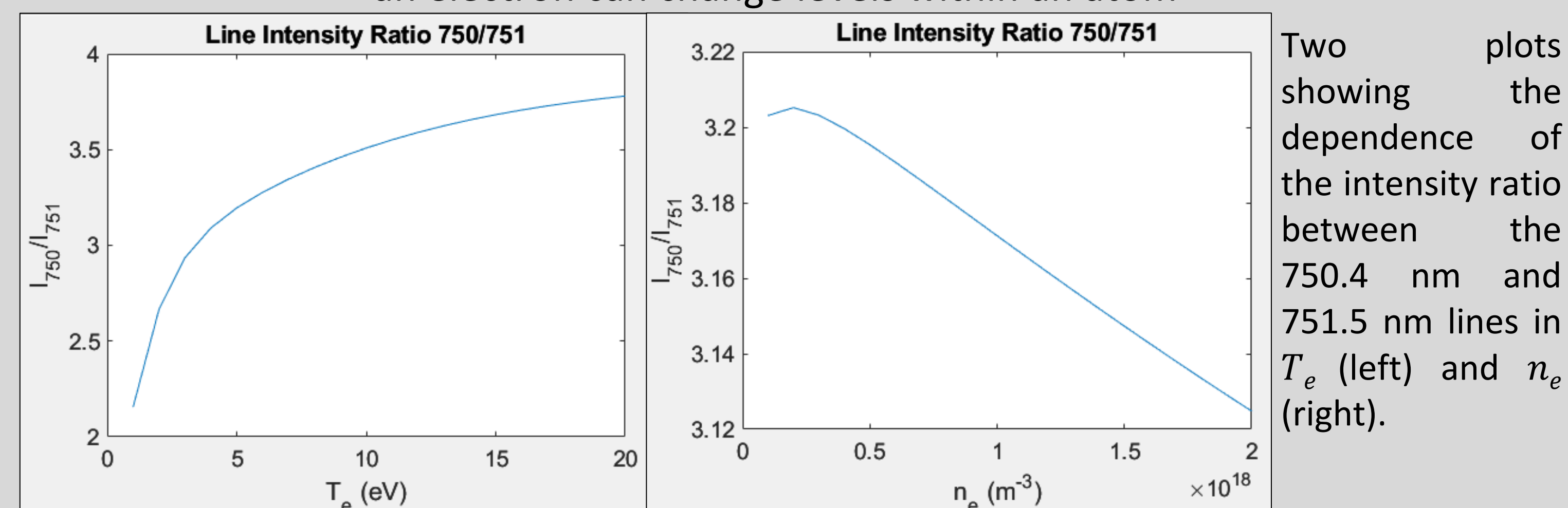
The Collisional-Radiative Model

To validate Hall thruster performance and lifetime models, *non-invasive optical measurements* are the preferred diagnostic tool, since direct probe measurement can perturb the plasma, decreasing their accuracy. While laser-induced fluorescence (LIF) is used to measure ion and neutral velocities with high resolution [4]; Optical emission spectroscopy (OES) can measure electron properties (but is currently less mature/accurate than LIF). OES measurements are simple, but deriving plasma properties such as electron temperature and density requires post-processing with a validated CR model. The CR model predicts population densities of atomic energy levels (and theoretical emission spectra) as a function of T_e , n_e , n_n , etc.; observed OES data are compared to the CR model to yield corresponding values of the electron plasma parameters. So far, a xenon CR model for Hall thrusters exists [1], but models for other gases (e.g. argon and krypton) are less developed. In this work, we have adapted the xenon model for use with argon, utilizing the relevant cross section data for argon to calculate the transition rates for use with the CR model's governing equation. The combination of the different processes allow us to calculate the population of a specific electron energy state k . The de-excitation rate of a state is calculated from the excitation rates using a detailed balance equation. When possible, experimental data was preferred over theoretical or calculated data, however, existing databases do not contain complete datasets for electron-impact ionization out of excited states, so the semi-empirical Deutsch-Mark formulation [7] was used to supplement the existing cross-sectional data for the electron-impact ionization.

$$\frac{dn_k}{dt} = \sum_{j \neq k} n_e n_j K_{jk} - \sum_{j \neq k} n_e n_k K_{kj} - n_e n_k K_{k,iz} + \sum_{j > k} n_j A_{jk} - \sum_{j < k} n_k A_{kj} + n_{Ar} + n_g K_{gk,Ar} + n_{Ar2} + n_g K_{gk,Ar2} +$$

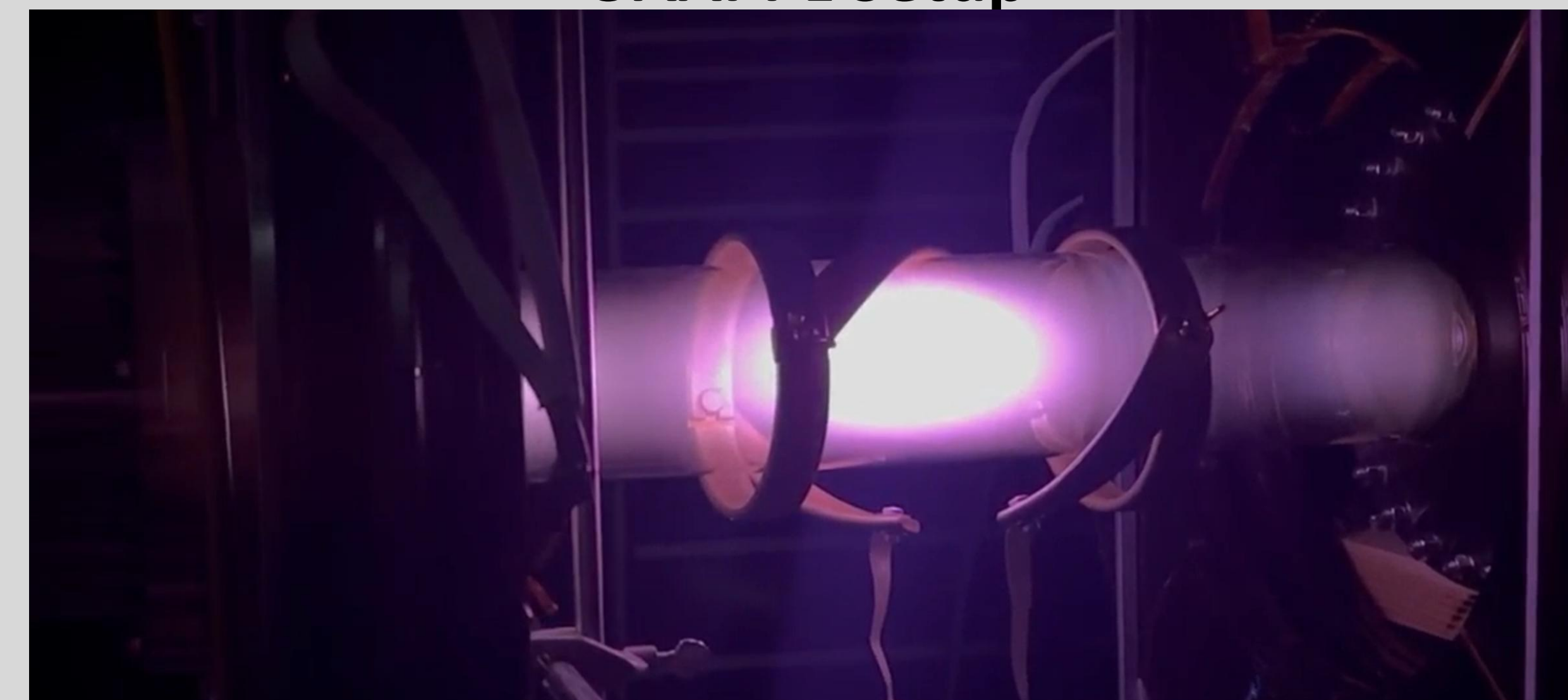
The effects of Ion-Impact Excitations are excluded in the Argon model (for now)

Governing Equation of the CR Model, calculating the different processes in which an electron can change levels within an atom



Grotrian Diagram showing most of the electron energy levels in the argon CR model, with the processes that produce particularly high intensity spectral lines outlined.

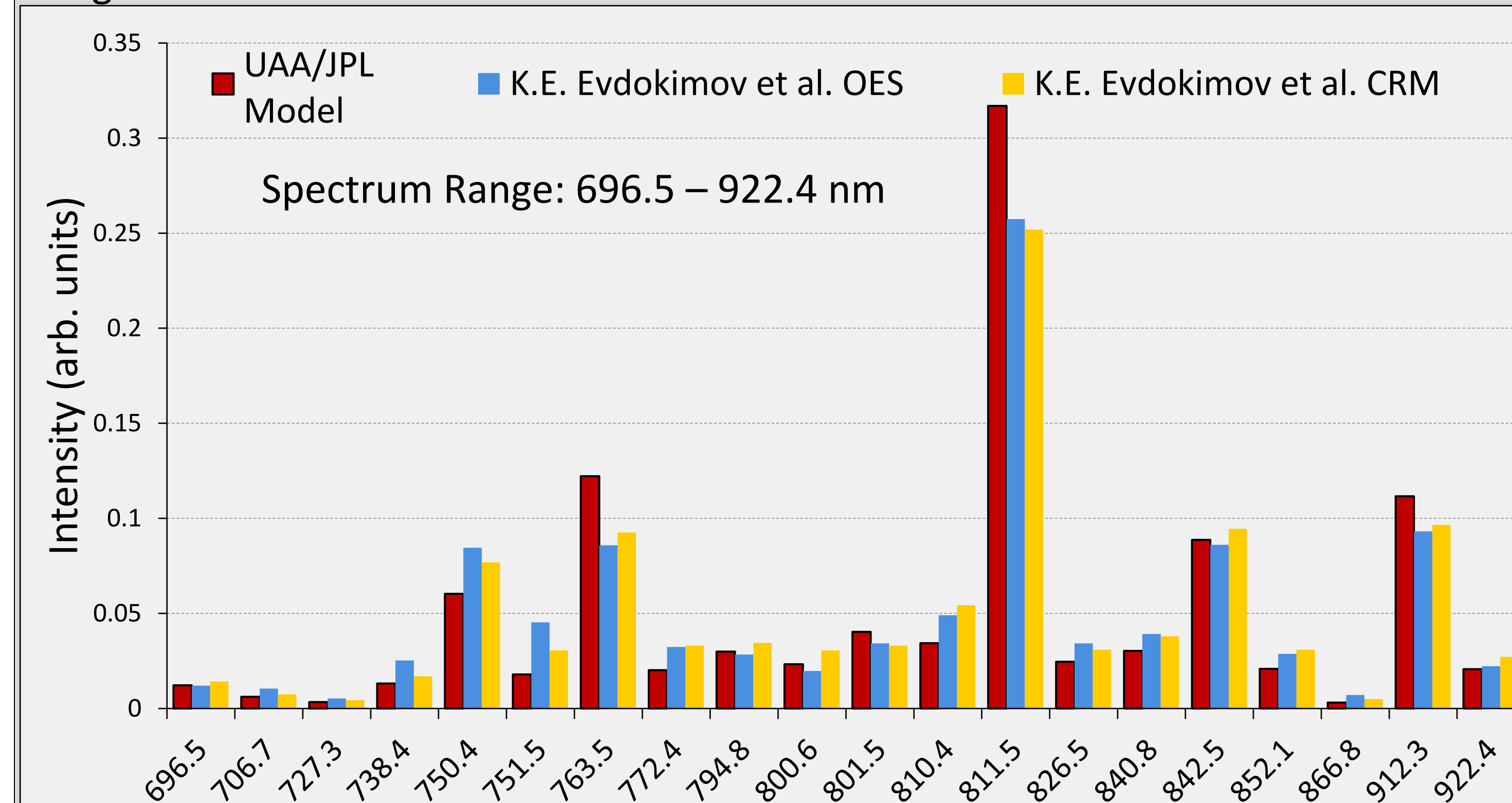
UAAPPL Setup



Experimental setup including RF plasma source for higher density plasma discharges [5], along with a supplementary anode layer ion source (ALIS) and optical fiber and lens for spectroscopy, with 2 magnetic field coil pairs on either end. OES is a line-averaged measurement, but collecting light along multiple chords through the plasma enables Abel inversion of the data to derive radial profiles.

Future Work and Model Validation

Preliminary results from the model are promising, with the comparatively extensive dataset perhaps contributing to the difference in results compared to other CR models in literature. A CR Model based on work from Gangwar et al. [3] created and validated by Evdokimov et al. [2] was used for comparison. The setup at UAAPPL allows further validation with our own data. The RF plasma source enables the levels of electron density and temperature common in electric propulsion contexts. Both a single and double Langmuir probe were constructed to directly measure the electron properties, which we will plug into the model. The model then produces a spectrum which can be compared to the experimental spectrum. We also hope to acquire a higher resolution spectrometer with higher range in the near infrared will allow more of the Ar lines to be measured.



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- Alaska URIS

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