Virtual Research Presentation Conference

Xenon Neutral and Ion Collisional-Radiative Models for Non-Invasive Hall Thruster Diagnostics

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Program: Innovative Spontaneous Concept

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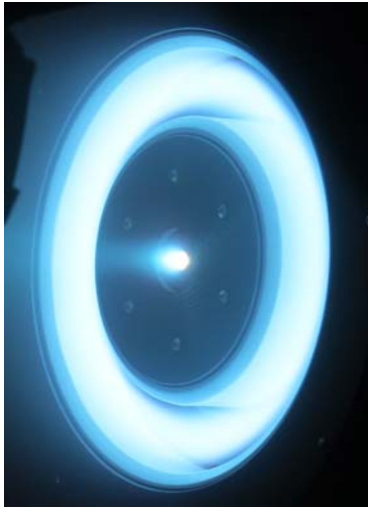
Tutorial Introduction

Abstract

The objective of this ISC R&TD effort was to construct collisional-radiative (CR) models for xenon plasmas that calculate the relative intensities of the brightest neutral (Xe I) and singly ionized (Xe II) emission lines as a function of electron temperature (T_e) and electron density (n_e). These models are needed to use optical emission spectroscopy (OES) to diagnose electron properties in Hall thrusters. Non-perturbing diagnostics such as OES can be used to validate the computational models that play a critical role in life qualification of thrusters for NASA missions. Using published collision cross section and transition rates from measurements [1-4] and theory [5-7], CR model scripts were built to solve the rate equations for the atomic level populations. Using the model outputs, simulated emission spectra were constructed, and promising Xe II emission lines for T_e and n_e measurements were identified. The Xe I model was validated against the predictions of an existing CR model by Dressler et al. [2], and previously unresolved density dependence in the emission line intensity ratios was identified. A time-dependent version of the Xe I model was also developed, enabling quantification of fundamental bandwidth limits for time-resolved measurements using Xe I line ratios.



Problem Description

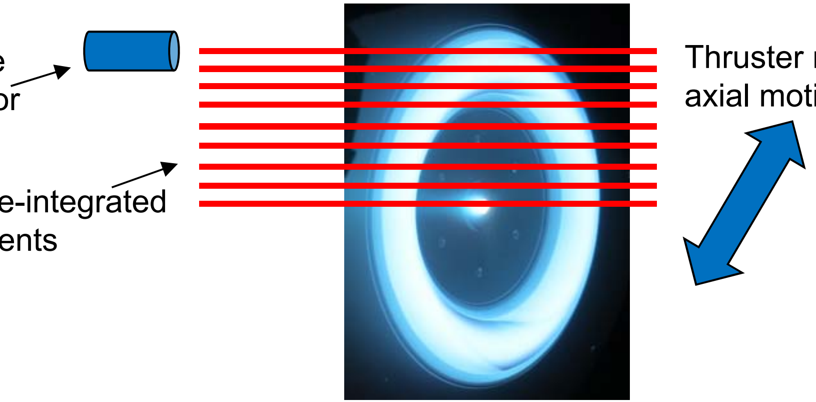
Context / Relevance to NASA and JPL: NASA's strategy for life qualification of Hall thrusters for deep space missions relies on a combination of long-duration wear tests and physics-based computational modeling; this approach is currently being applied to the 12.5 kW HERMeS thruster for the Advanced Electric Propulsion System, the 4.5 kW SPT-140 thruster for Psyche, and the 1 kW MaSMi thruster. Validation experiments involving plasma measurements in the thruster channel and near plume play a critical role in the modeling process, increasing confidence in the reliability of the simulations and supplying information to guide model improvements when needed. At present, JPL has a well-developed technique for measuring the time-averaged and time-resolved ion dynamics using laser-induced fluorescence (LIF). However, a comparable capability for non-perturbing measurements of electron properties such as density (n_e) and temperature (T_e) has been lacking. Developing ways to make these measurements is especially important because electron physics (in particular cross-field transport) is the least well-understood aspect of Hall thruster operation, and knowledge of these quantities is needed to improve the accuracy of the simulations.

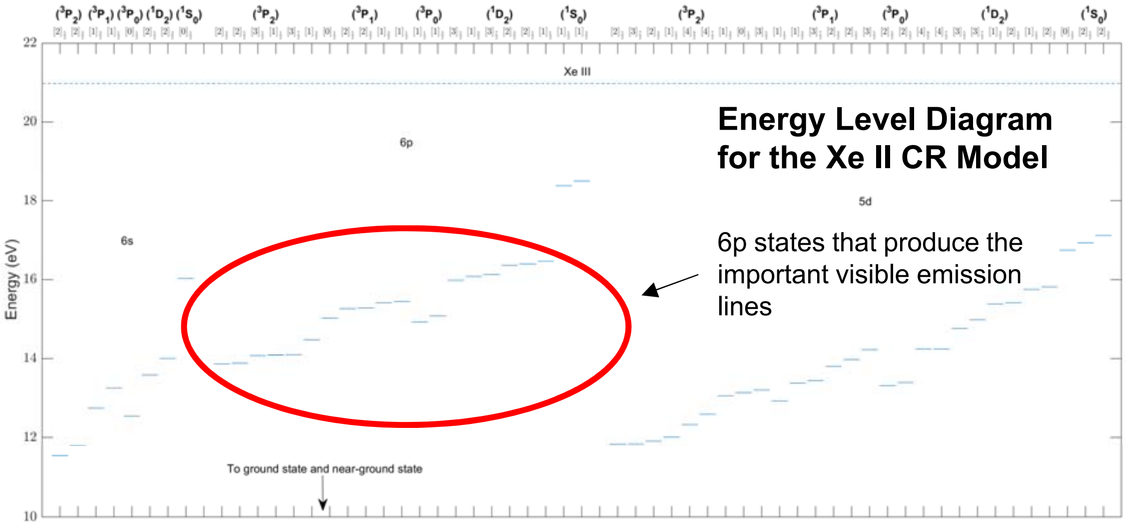
Problem Description

SOA: The CR model for neutral xenon (Xe I) near-infrared emission published by Karabadzhak, Chiu, and Dressler et al. [2,8], often known as the "KCD" model, has been the SOA for Hall thruster OES analysis for over a decade. This model has proven useful for diagnosing the plume plasma, but it has not been able to support accurate measurements in the acceleration region, where the electron behavior is most complex. Recently, theoretical calculations of electron-impact excitation cross sections for singly ionized xenon (Xe II) were published by Wang et al. [5], for the first time enabling construction of a CR model for Xe II. In this work, we have developed such a model, which was expected to provide improved sensitivity to T_e and n_e in hot, dense regions of the plasma. To validate the approach, a Xe I model was also constructed using theoretical cross sections calculated by the same method that produced the Xe II cross sections [6]. This model included phenomena that were neglected in the KCD model, and new results were obtained, including n_e dependence and insight into time-varying emission during Hall thruster oscillations.

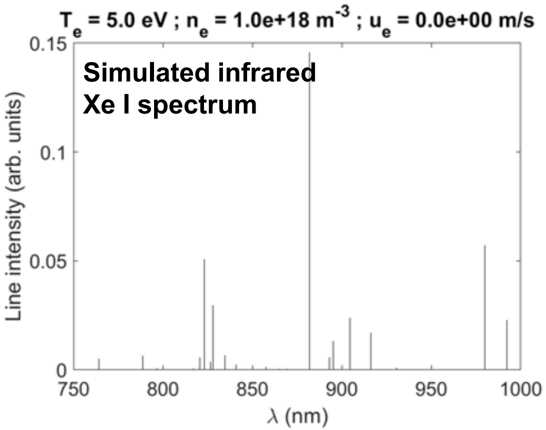
Methodology

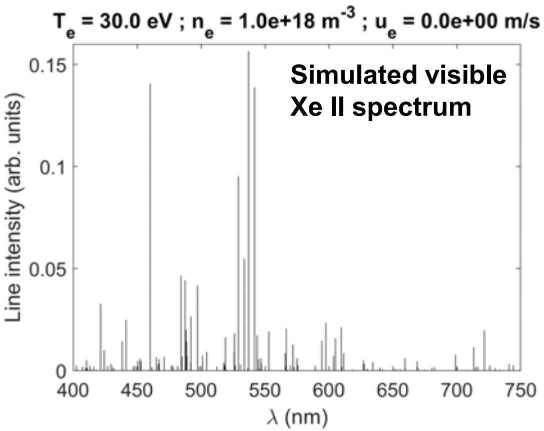
- OES is a line-integrated diagnostic, but spatial resolution can be achieved in axisymmetic thrusters using Abel inversion.
    - Modern magnetically shielded thrusters have the acceleration region downstream of the channel exit, facilitating optical access.
- The CR models included 36 excited states for Xe I and 57 excited states for Xe II.
    - Atomic processes accounted for in the rate equations included electron-impact excitation and de-excitation, electron-impact ionization, spontaneous decays, ion-impact excitation, electron-impact ionization-excitation.





Results

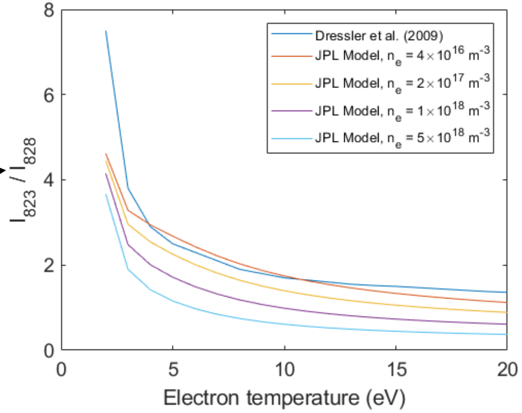




- The main goals of the project were accomplished: Xe I and Xe II CR models were constructed and tested, applications were explored, and limitations on the applicability of the models were analyzed.

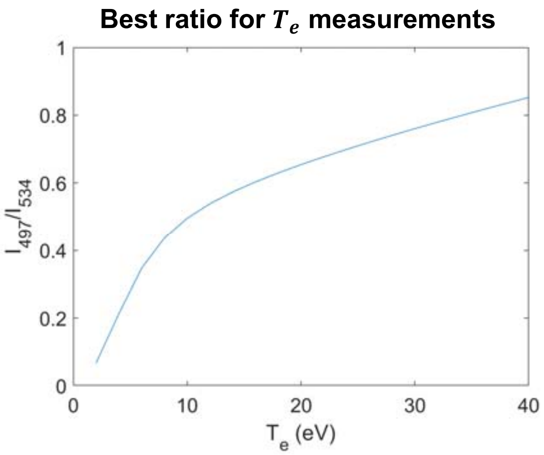
- Simulated emission spectra such as those shown here can be compared with spectroscopy data, using either intensity ratios of two lines, or least squares minimization to find the plasma parameters for which the simulated spectrum best matches the data overall.

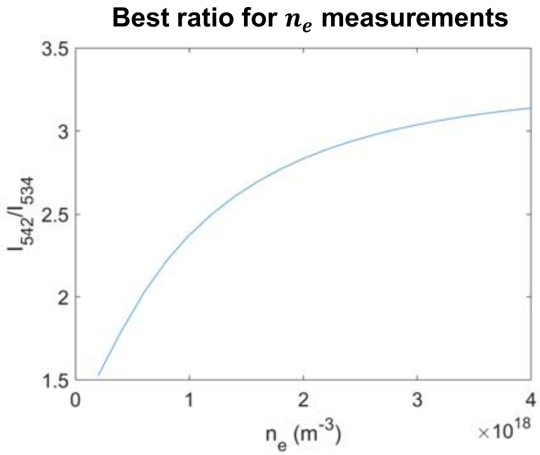
- The Xe I model was validated against previously published results from a model by Dressler et al. that used mostly experimental cross sections [2], yielding good agreement in the low-electron density limit.
  - At higher n_e, stepwise ionization neglected in Ref. [2] can significantly alter the [823 nm]/[828 nm] and [835 nm]/[828 nm] ratios, potentially explaining why the older model produced unreasonably high T_e results inside the discharge channel.



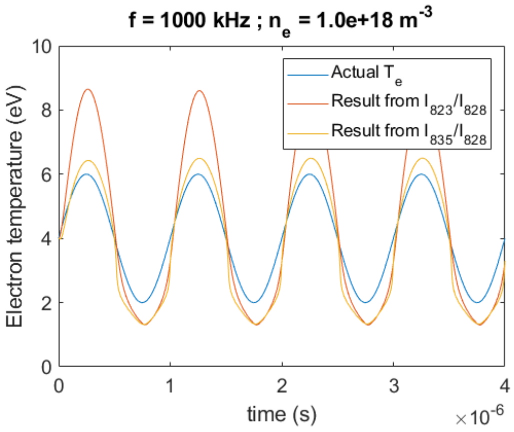
Results

- Optimal Xe II line ratios for T_e and n_e measurements were identified. Criteria included:
  - Lack of strong contaminating lines within 1 nm, strong dependence on only one variable (T_e or n_e), lack of sensitivity to convection of metastables





- The time-dependent version of the Xe I mode revealed fundamental bandwidth limitations for accurate high-frequency temperature measurements imposed by the sluggish response of the metastable atom population to changes in local plasma properties.



- Undergraduate and graduate intern projects this summer have been continuing CR model development and validation.
- A key next step will be validation experiments comparing T_e and n_e derived from OES using the Xe II CR model with results from Langmuir probe measurements.

References

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