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Laboratory Astrophysics on ASDEX Upgrade: Measurements and Analysis of K-Shell O, F, and Ne Spectra in the 9-20 A region

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Laboratory astrophysics on ASDEX Upgrade: Measurements and analysis of K-shell O, F, and Ne spectra in the $9 - 20$ Å region

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ABSTRACT

High-resolution measurements of K-shell emission from O, F, and Ne have been performed at the ASDEX Upgrade tokamak in Garching, Germany. Independently measured temperature and density profiles of the plasma provide a unique test bed for model validation. We present comparisons of measured spectra with calculations based on transport and collisional-radiative models and discuss the reliability of commonly used diagnostic line ratios.

1. Introduction

Ratios of K-shell emission lines are commonly used to diagnose temperatures (T_e) and densities (n_e) of astrophysical plasmas. While simple line ratios can give quick estimates of uniform plasma conditions, they may have limited utility for diagnosing integrated spectral measurements from plasmas with gradients or non-equilibrium ion distributions. With modern simulation capabilities and independent laboratory diagnostics, tokamaks can help validate sophisticated models for complex, astrophysically relevant plasma environments. We

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have modeled K-shell emission spectra from an H-mode discharge of the ASDEX Upgrade tokamak using the transport code STRAHL, which predicts ion distributions accounting for transport processes, and the collisional-radiative code SCRAM, which uses these ion distributions to create synthetic spectra. The agreement of synthetic and experimental spectra is quite good, demonstrating the value of tokamak data as a benchmark for laboratory astrophysics. Comparisons of simple line ratios from two independent atomic models, SCRAM and ATOMDB, are also presented and their utility as diagnostics for complex plasmas is discussed.

2. ASDEX Upgrade data and models: benchmark comparison

The ASDEX Upgrade device at the Max-Planck Institute für Plasmaphysik is a midsized tokamak divertor tokamak with a major radius of $R = 1.65$ m and a poloidal radius of $a = 0.5$ m [Herrmann and Gruber (2003)]. The plasma can reach temperatures up to 4 keV and densities near $10^{14}\mathrm{cm}^{-3}$ at its center. Radial profiles of n_e and T_e are obtained by interferometers, analysis of the excitation profiles of a radial lithium beam, Thomson scattering (VTA), and measurements of electron cyclotron emissions (ECE) – see Fig. 1. Spectral emission in the 9 – 20 Å region is collected using a Bragg crystal spectrometer [Bolshukhin et al. (2001)]

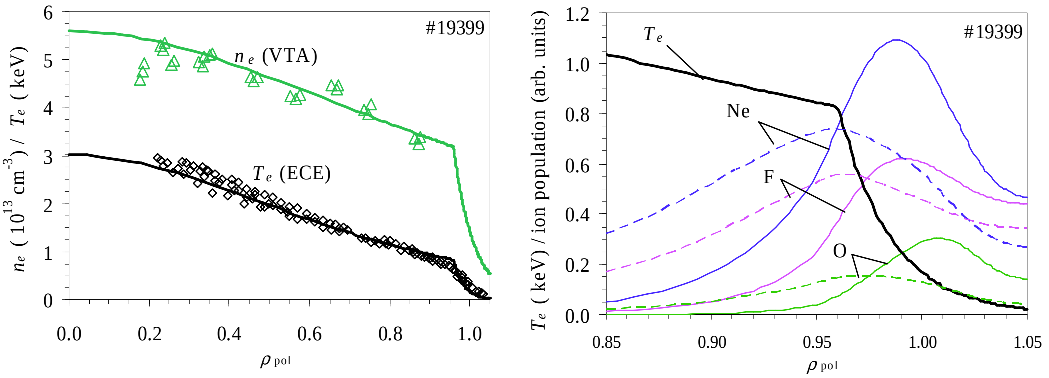

Fig. 1.— Left: measured n_e and T_e along the poloidal axis. Right: He-like (solid) and H-like (dashed) ion populations from STRAHL in the radiating region $\rho_{pol} = 0.85 - 1.05$.

Since in the hot center of the plasma, O, F, and Ne atoms are fully stripped, the measured emission from H- and He-like O, F, and Ne ions originates from the edge region of the plasma. The local distributions of these impurity ions in the edge region are strongly influenced by plasma transport, which shifts emitting ions to regions of higher T_e than they would be found in a transportless equilibrium. The STRAHL program quantifies this deviation from equilibrium. Following previous investigations on the transport parameters of ASDEX Upgrade plasmas [Dux (2003)], and using typical diffusion coefficient profiles (0.5 to 2.0 m^2/s) and drift velocity profiles (time averaged values with a maximum inward drift velocity of 8 m/s at a narrow radial region) along with the measured T_e and n_e profiles, STRAHL combines plasma transport with the rate equations for ionization and recombination of impurity ions to predict the non-equilibrium charge state distribution. The steady-state of the impurity distribution was found by taking a constant impurity source for constant plasma conditions. Figure 1 shows the measured T_e and n_e profiles and the resultant relative populations of H- and He-like ions for the three impurity elements. We note that predictions for the radial position of abundance maxima involve considerable uncertainties at the edge of a tokamak plasma, where gradients of plasma and transport parameters change dramatically within a few cm. However, because the line of sight is performing a radial integral, variations in these parameters within the uncertainties do not change the basic results of the modeling.

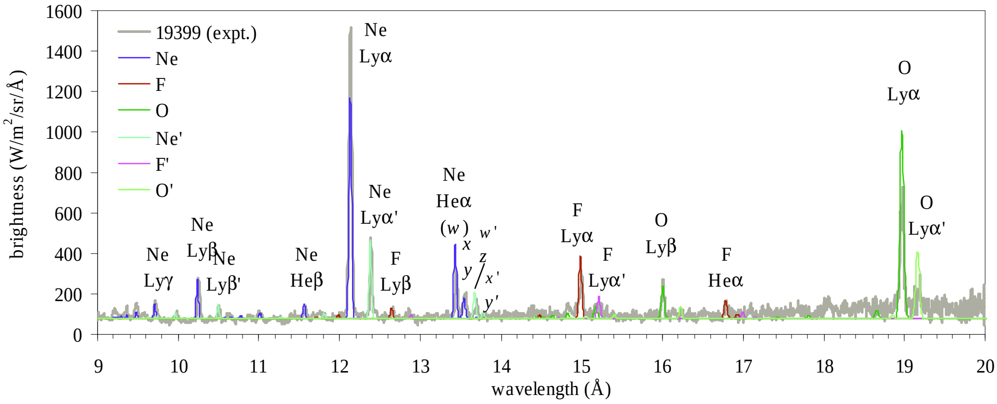

Fig. 2.— Comparison of modeled and experimental spectra for the H-mode shot 19399. Lines marked with ′ are spectrometer artefacts. High-intensity lines may be saturated.

Once STRAHL has determined ion distributions, we generate synthetic spectra using the collisional-radiative kinetics model SCRAM [Hansen (2003)]. SCRAM is based on data from the Flexible Atomic Code FAC [Gu (2003)] and includes all collisional and spontaneous processes among and between ions. The models for Ne, F, and O include singly excited states up to $n = 10$ in H- and He-like ions and $n = 6$ in Li- and Be-like ions, and doubly excited states up to $n = 4$ in He-, Li- and Be-like ions. Collisional ionization rates were modified to enforce the transport-influenced ion distributions given by STRAHL while retaining the accuracy of a full collisional-radiative treatment. The final spectrum, generated by integrating emission along the spectrometer line of sight, agrees quite well with the experimental data, as shown in Fig. 2.

3. Equilibrium line ratios and model comparison

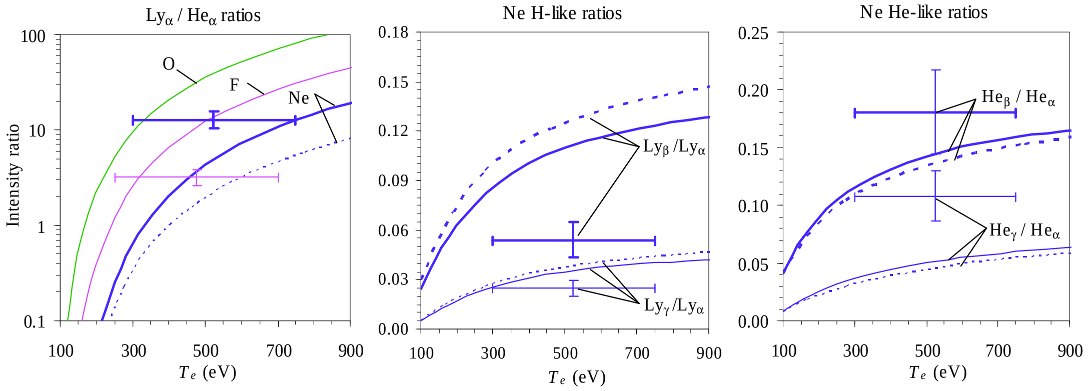

Fig. 3.— T_e-dependent Ly_α/He_α ratios for O, F, and Ne ions with equilibrium ion distributions from SCRAM (solid) and ATOMDB (dashed). Error bars on the experimental points indicate the T_e range separating STRAHL predictions for H- and He-like abundance maxima.

Figure 3 shows equilibrium T_e-dependent diagnostic line ratios from independent collisional-radiative models SCRAM and ATOMDB [Smith (2001)]. While the T_e values diagnosed using experimental Ly_α/He_α ratios would at least fall within the measured T_e range, the intra-ion ratios are of little diagnostic utility due to the strong temperature gradient. The collisional excitation rates of the two models agree to within 15% in the given temperature range; this agreement is reflected in the given intra-ion ratios. The disagreement between SCRAM and ATOMDB for the Ly_α/He_α ratio is mostly due to differences in the model predictions for the ionization distribution.

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