Reaching Higher Densities for Laboratory White Dwarf Photospheres to Measure Spectroscopic Line Profiles

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Abstract. As part of our laboratory investigation of the theoretical line profiles used in white dwarf atmosphere models, we extend the electron-density ($n_e$) range measured by our experiments to higher densities (up to $n_e \sim 80 \times 10^{16}$ cm$^{-3}$). Whereas inferred parameters using the hydrogen-$\beta$ spectral line agree among different line-shape models for $n_e \lesssim 30 \times 10^{16}$ cm$^{-3}$, we now see divergence between models. These are densities beyond the range previously benchmarked in the laboratory, meaning theoretical profiles in this regime have not been fully validated. Experimentally exploring these higher densities enables us to test and constrain different line-profile models, as the differences in their relative H-Balmer line shapes are more pronounced at such conditions. These experiments also aid in our study of occupation probabilities because we can measure these from relative line strengths.

1. Introduction

Theoretical line profiles are a critical ingredient of white dwarf (WD) atmosphere models (e.g., Koester et al. 1979; Bergeron et al. 1992; Koester 2010). A modification to the hydrogen line profiles by Tremblay & Bergeron (2009) resulted in significant systematic changes to the inferred WD atmospheric parameters (i.e., effective temperature, $T_e$, and surface gravity, $\log g$) from Liebert et al. (2005). These H line profiles have since become the standard in the community and in the comprehensive analysis of thousands of WDs (e.g., Tremblay et al. 2011; Girven et al. 2011; Gianninas et al. 2011; Kleinman et al. 2013; Limoges et al. 2015; Guo et al. 2015).

Though this spectroscopic method is powerful, precise, and widely used, its results do not agree with mass determinations using gravitational redshifts (Barstow et al. 2005; Falcon et al. 2010b) nor inferred atmospheric parameters using photometry (Genest-Beaulieu & Bergeron 2014). For this latter example, H line profiles are specifically a suspect for the disagreement.

We thus experimentally investigate the spectroscopic method by targeting the theoretical line profiles used in WD atmosphere models. We have performed laboratory experiments at the Z Pulsed Power Facility (e.g., McDaniel et al. 2002; Matzen et al. 2005; Rose et al. 2010; Savage et al. 2011) at Sandia National Laboratories to measure the spectral line profiles present in the high-density ($n_e$) plasmas of WD photospheres
Having achieved higher densities in the laboratory than previously explored in this way—while measuring multiple spectral lines simultaneously—we now extend our measurements to plasmas at even higher $n_e$. This allows us to better discriminate amongst theoretical line profiles, since relative line shapes (i.e., among Balmer lines) differ between calculations with increasing principal quantum number (Tremblay & Bergeron 2009) and with increasing $n_e$. We can also uniquely investigate occupation probabilities (Hummer & Mihalas 1988) by measuring relative line strengths.

2. Experiment

To reach higher electron densities, we adjust the gas-fill pressure of our gas cell. We also spectroscopically observe the plasma generated inside our cell (Rochau et al. 2014) along a line of sight that is closer (5 mm instead of our standard 10 mm) to the gold wall from which the photoionizing radiation emerges (see Falcon et al. 2015).

![Figure 1](image-url)  
**Figure 1.** Electron density, $n_e$, as a function of time throughout our experiments z2553 and z2832. We infer $n_e$ using different theoretical line-profile calculations.

Figure 1 shows our inferred $n_e$ as a function of time throughout two experiments. The onset of backlighting continuum emission that allows us to measure absorption spectra of our plasma (Falcon et al. 2013a) occurs at 0 ns. We include data from experiment z2553 (Falcon et al. 2015), from which we infer consistent values by fitting our measured H$\beta$ spectral line while using different theoretical line-profile calculations. We
now report data from experiment z2832, whose $n_e$ increases beyond that of z2553 by approximately a factor of three. At these higher electron densities ($n_e \gtrsim 30 \times 10^{16} \text{ cm}^{-3}$), we see a systematic divergence among the $n_e$ inferred from different theoretical line profiles.

The calculations we use to determine $n_e$ are those of Lemke (1997) (which follow the theory of Vidal et al. 1973, VCS), Tremblay & Bergeron (2009, TB), Gigosos et al. (2003, GGC), and Xenomorph (XENO; see Ferri et al. 2014; Gomez et al. 2016b,a). These first two are semi-analytic calculations often used in WD atmosphere models. These latter two both follow a computer-simulation approach (e.g., Stamm et al. 1984) and have not been used for WD analysis. We do not include inferences using GGC profiles beyond $\sim 20 \times 10^{16} \text{ cm}^{-3}$ because the authors do not claim validity at values greater than that. We still plot GGC inferences less than $\sim 20 \times 10^{16} \text{ cm}^{-3}$ (even though the plotted symbols lie underneath those using other calculations) because they give credence to Xenomorph, the other computer-simulation calculation. Note by how far we exceed the maximum $n_e$ achieved by the benchmark experiment of Wiese et al. (1972), the only other experiment that measured multiple H Balmer lines near these plasma conditions.

![Figure 2](image.png)

**Figure 2.** Measured Hβ spectral transmission at 80–90 ns during experiment z2832. We fit using different theoretical line-profile calculations ($n_e \sim 83$, $\sim 93$, and $\sim 76 \times 10^{16} \text{ cm}^{-3}$ for VCS, TB, and XENO, respectively) and show the goodness of fit (reduced $\chi^2$).

Figure 2 shows a fit to our measured Hβ line integrated from 80 to 90 ns during experiment z2832. Here, the spectral line becomes quite wide because the electron den-
sity is so high \( (n_e \sim 80 \times 10^{16} \text{ cm}^{-3}) \). Also, asymmetry in the line profile—an effect that is rarely considered in WD synthetic spectra (Halenka et al. 2015)—becomes apparent. Xenomorph is the only calculation we use whose profiles are asymmetric because it includes greater detail when solving for the Coulomb potential of the radiators in a plasma (Gomez et al. 2016b). This causes the goodness of fit (reduced \( \chi^2 \)) to surpass that of VCS and TB. A reduced \( \chi^2 \) as low as we show here indicates that we overestimate the noise level, which determines the uncertainties plotted for each spectral point (Falcon et al. 2015).

3. Discussion

The systematic disagreement between our \( n_e \) inferences using different line-profile calculations is small at the lower values of experiment z2553, but it is apparent and greater than the measurement uncertainties at the higher values of experiment z2832. This is troubling because we fit the measured H\( \beta \) line to diagnose our plasma conditions. We chose it for two reasons: (1) because its theoretical line profiles agree with one another at these lower densities, and (2) because the H\( \beta \) spectral line has been validated by benchmark experiments (Kelleher et al. 1993).

While a few benchmark H-line-profile experiments have reached electron densities greater than \( n_e = 10 \times 10^{16} \text{ cm}^{-3} \) (e.g., McLean & Ramsden 1965; Baessler & Kock 1980; Helbig & Nick 1981, who achieve \( n_e \sim 28, \sim 16, \) and \( \sim 14 \times 10^{16} \text{ cm}^{-3} \), respectively), the highest density achieved by one that measures multiple lines is that by Wiese et al. (1972), who reach \( n_e \sim 9 \times 10^{16} \text{ cm}^{-3} \); measuring multiple lines to test relative line shapes and strengths is a critical requirement for our laboratory investigation of theoretical line profiles (Falcon et al. 2015). Our experiment now has the capability of verifying line-profile calculations at these high electron densities.

4. Ongoing Work

As our experiments continue to evolve, our scientific direction branches out into multiple directions:

- Absorption lines at high densities are not explicitly apparent in most observed WD spectra because they do not exist at the outer radii of WD photospheres (Hubeny & Lanz 1995). They are important in the integration over the vertical structure of the atmosphere, though, which includes a broad range of densities (Hubeny et al. 1994), and more so for massive WDs (e.g., Hermes et al. 2013). To determine the preferred theoretical line profiles to insert into WD atmosphere models, we are now including different ones into atmosphere calculations.

- Because we spectroscopically observe line profiles in absorption, our measured Balmer lines share the same lower-level population. Using published oscillator strengths (Baker 2008), this permits us to compare relative line strengths between Balmer lines as a way to directly extract occupation probabilities. We can then compare our measurements with calculations (i.e., Seaton 1990).

- We now expand our laboratory experiments to other compositions relevant to WD photospheres (Falcon et al. 2013b). Schaeuble et al. (2016) show data measured from helium plasmas, which can be used to test not only theoretical He
line broadening (e.g., Beauchamp et al. 1997), but also line shifts relevant to gravitational-redshift work (Falcon et al. 2012). We also now create carbon plasmas whose measured lines can be used to test the theoretical line profiles used in atmosphere models for carbon-dominated WDs (Dufour et al. 2011).

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