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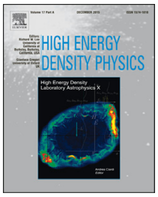

An experimental platform for creating white dwarf photospheres in the laboratory: Preliminary results

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ABSTRACT

We present the current status of the White Dwarf Photosphere Experiment at the Z Pulsed Power Facility at Sandia National Laboratories. This experiment has evolved into a unique platform for simultaneously measuring emission, absorption, and back-lighter continua spectra of plasmas with white dwarf (WD) photospheric compositions and conditions (T_e~1 eV, n_e~10^{16}–10^{18}e/cm^3); our current experiments involve line profile measurements of hydrogen—corresponding to the most common surface composition in white dwarf stars, with future experiments planned for helium, carbon, and oxygen. These profiles will test line broadening theories used in white dwarf model atmospheres to infer the fundamental parameters (e.g., effective temperature and mass) of thousands of WDs. This experiment uses the large amount of x-rays generated from a z-pinch dynamic hohlraum to radiatively drive plasma formation in a gas cell. We reach significantly higher densities than the landmark study of Wiese et al. (1972), thereby putting competing line broadening theories to the test in a regime where their predictions strongly diverge. The simultaneous measurement of emission, absorption, and back-lighter continua in macroscopic plasmas represents a significant advance relative to hydrogen line profile experiments of the past.

1. Introduction

While the diagnostic value of Stark-broadened lines such as Hβ has long been appreciated by the experimental physics community, it is perhaps less well known that these lines also play a significant role in inferring the plasma conditions at the photospheres ("surfaces") of high gravity astronomical objects. Particularly for the white dwarf stars (WDs), whose gravities are ~10^4 times higher than that of the Sun, their correspondingly higher electron densities (n_e~10^{16}–10^{18}e/cm^3) lead to significant Stark broadening of the lines. Exploiting this sensitivity, astronomers use the measured widths of these lines to infer the surface gravities of these WDs, and thereby determine their masses [e.g., [1]]. This technique is referred to as the "spectroscopic method".

The spectroscopic method is the most widely-used technique and is responsible for determining parameters for tens of thousands of WDs [e.g., [2–7]]. Obtaining high accuracy estimates of these parameters is crucial for the use of WDs in many areas of research, such as determining the age of the Universe [8], constraining the mass of supernova progenitors [e.g., [9]], and probing properties of dark matter axions [10].

Two works on line broadening have historically been fundamental in the white dwarf field: the landmark measurements of Stark-broadened hydrogen lines by Wiese et al. [11] and the "unified theory" of Vidal-Cooper-Smith [VCS, [12,13]]. This "unified theory" is so-called because it unifies the calculations of the line center (in the "impact limit") with those of the line wings (the "quasi-static limit"). This analytical model has been applied to calculations of hydrogen lines [VCS, [12]] and was the main one used in analyzing WD spectra for the next several decades.

In the early 1990's, Schoning (1994) [14] and Napiwotzki & Rauch (1994) [15] examined the importance of including NLTE effects in WD atmosphere models; due to the averaging of the emergent flux over a stratified atmosphere with a range of densities and temperatures, they concluded that the detailed features of the NLTE line shapes were lost and that there was no significant effect. As a result, VCS theory continued to be the only treatment used in WD model atmospheres for the next 15 years.

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This changed in 2009 as Tremblay & Bergeron [16] developed a new treatment of line broadening that included non-ideal effects. These non-ideal effects are taken into account using the Hummer and Mihalas [17] equation of state, and are directly incorporated into their line profile calculations. When implemented in a model atmosphere code, they found this led to revisions of ~500–1000 K in temperature and 5–10% in mass for the population of WDs.

In addition, line profile techniques have been developed that are based on direct simulation: particle simulations are used to compute the electric fields felt by the emitting atom and the Schrödinger equation is then numerically integrated [e.g., see Refs. [20,21]]. This allows one to simultaneously include many effects that are awkward analytically, such as ion motion (the "quasi-static approximation") and the coupling between states not directly involved in the transition (the "no-quenching approximation"). While widely used as diagnostics for laboratory plasmas, these profiles have not yet been used to model the observed spectra of WD stars.

Finally, Falcon et al. [19] used an independent technique involving gravitational redshift to measure the mean mass of a sample of WDs. They similarly found a ~10% increase in the mean mass of their sample. In Fig. 1 we show these data with the stars binned by mass. Over a broad range of masses we see that the gravitational redshift mass is significantly higher than the spectroscopic mass. Given that the average spectroscopic WD mass is ~$0.6M_\odot$, this plot shows the gravitational mass is indeed about 10% higher.

With new advances in theory [e.g.,[16,20–22]], new experimental capabilities available at modern facilities [23], and a wealth of spectroscopic observations that did not exist much more than a decade ago [e.g., [3]], the time is right for a re-examination of theoretical and experimental underpinnings of WD model atmospheres.

2. Platform on Z

We note that while this section and the following sections present preliminary aspects and results of our experiment on Z, a more complete and thorough analysis will soon be submitted for publication [24].

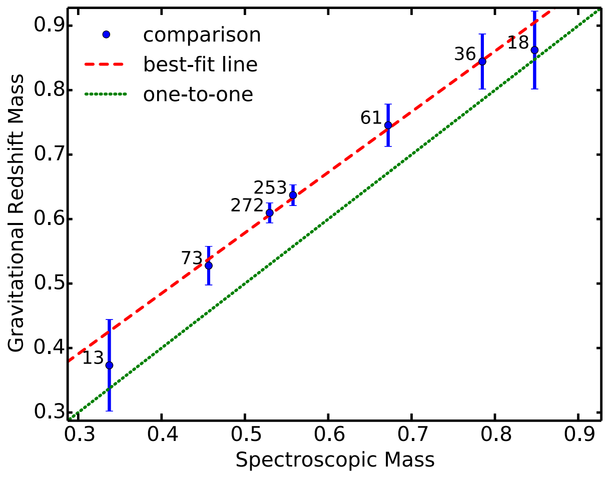

Fig. 1. Comparison of the masses of white dwarfs as determined from gravitational redshift measurements and spectroscopic line profile fits. The data were taken from the SPY survey [18,4] as analyzed by Falcon et al. [19] and were placed into mass bins based on their spectroscopic masses. Each data point is labeled with the number of stars in that bin, and the error bars represent the uncertainty in gravitational mass due to the sample size.

2.1. The "ACE" design

The current design for our gas cell platform is called the "ACE" design, which stands for Absorption, Continuum, and Emission (see Fig. 2). The plasma forms inside a rectangular central cavity that is 12 × 3 × 2 cm. A Mylar window faces the z-pinch x-rays and interfaces between the vacuum chamber containing the experiment and the pressurized gas cell. Buffers provide spatial separation between the collection optics (inside the optics shield) and the hot plasma.

Inside the central cavity a stainless steel plate coated with 5 μm of gold lines the back wall. A polyhedral stainless steel block, also coated with 5 μm of gold, rests on one end. The surface of this block is tilted with respect to the plane normal to the z-pinch x-rays and pitched with respect to the horizontal plane. This allows the x-rays, the optics in one of the horizontal lines of sight (LOS), and the optics in the vertical LOS to each have a direct view of this surface. The x-rays heat up this gold surface just as they do the back wall, allowing it to function as a back-lighting surface for absorption measurements.

For more details concerning this design see Falcon [25].

2.2. Radiative transfer

We use three independent lines of sight to disentangle the effects of radiative transfer in our plasma.

For simple one-dimensional radiative transfer in a uniform plasma we can write

$$\frac{dI_\nu}{dx} = -\rho\,\kappa_\nu I_\nu + \rho\,\varepsilon_\nu, \tag{1}$$

where I_ν is the intensity of the radiation field, ρ is the mass density of the gas, and κ_ν and ε_ν are the opacity and emissivity per unit mass, respectively [see, e.g., [26]]. The subscript ν indicates that the quantities are functions of the frequency of the radiation field. Solving Equation (1), assuming a uniform plasma of length L, yields

$$I_\nu(L) = \underbrace{e^{-\rho\,\kappa_\nu L} I_\nu(0)}_{\text{absorption}} + \underbrace{\frac{\varepsilon_\nu}{\kappa_\nu}\left(1 - e^{-\rho\,\kappa_\nu L}\right)}_{\text{emission}}, \tag{2}$$

where we have labeled the components due to absorption and emission. The observable quantity is $I_\nu(L)$, and we can see that it

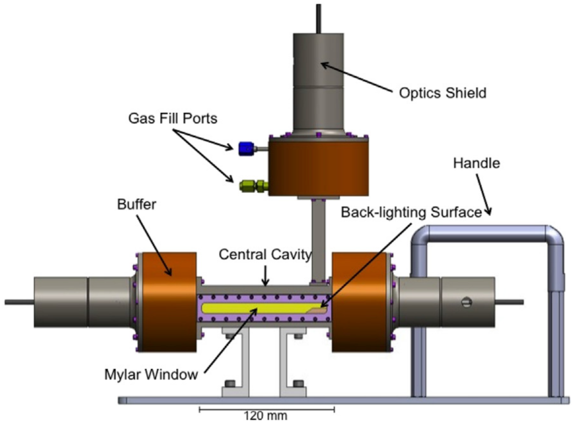

Fig. 2. Front view drawing of a gas cell assembly. Two horizontal lines of sight observe the plasma in emission and in absorption while a third, vertical line of sight observes the back-lighting continuum emission from the gold reflector. This design, with its three lines of sight, allows us to make simultaneous measurements of the plasma emission and absorption, and the back-lighter continuum.