An Experimental Platform for Creating White Dwarf Photospheres in the Laboratory: Preliminary Results

M. H. Montgomery^a, Ross E. Falcon^{a,b}, G. A. Rochau^b, J. E. Bailey^b, T. A. Gomez^{a,b}, A. L. Carlson^b, D. E. Bliss^b, T. Nagayama^b,
M. Stein^a, D. E. Winget^a

^a*Department of Astronomy and McDonald Observatory, University of Texas, Austin, TX 78712, USA*

^b*Sandia National Laboratories, Albuquerque, NM 87185-1196, USA*

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 ($T_e \sim 1$ eV, $n_e \sim 10^{16}$ – 10^{18} e/cm³); 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.

Keywords: laboratory experiments, astrophysics, hydrogen line profiles, stellar atmospheres, white dwarf stars

1. Introduction

While the diagnostic value of Stark-broadened lines such as H β 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 $\sim 10^4$ times higher than that of the Sun, their correspondingly higher electron densities ($n_e \sim 10^{16}$ – 10^{18} e/cm³) 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, 3, 4, 5, 6, 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.

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 20, 21]. This allows one to simultaneously include many effects that are awkward analytically, such as ion motion (the

Email address: mikemon@astro.as.utexas.edu (M. H. Montgomery)

Figure 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.

“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 $\sim 10\%$ increase in the mean mass of their sample. In Figure 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 $\sim 0.6M_{\odot}$, this plot shows the gravitational mass is indeed about 10% higher.

With new advances in theory [e.g., 20, 16, 22, 21], 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].

2.1. The “ACE” design

The current design for our gas cell platform is called the “ACE” design, which stands for Absorption, Continuum, and

Figure 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.

Emission (see Figure 2). The plasma forms inside a rectangular central cavity that is $12 \times 3 \times 2$ 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 $5\mu\text{m}$ of gold lines the back wall. A polyhedral stainless steel block, also coated with $5\mu\text{m}$ 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

$$\frac{dI_{\nu}}{dx} = -\rho \kappa_{\nu} I_{\nu} + \rho \epsilon_{\nu}, \quad (1)$$

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 eqn. 1, assuming a uniform plasma of length L , yields

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

Figure 3: Preliminary fits of different models (colored lines) to a measurement of $H\beta$ (points with errorbars). These fits infer very similar values for the free electron density (n_e) and the $n = 2$ population (n_2). The main differences in theories are in the line core; see Falcon et al. [24] and Falcon [25] for a more detailed view.

where we have labeled the components due to absorption and emission. The observable quantity is $I_\nu(L)$, and we can see that it depends on three unknown quantities: κ_ν , ϵ_ν , and $I_\nu(0)$. $I_\nu(0)$ represents the back-lighter intensity (continuum). By taking data along three different lines of sight, with different lengths L , we can solve for each of these unknown functions.

The first LOS is 12 cm long and is backlit by a heated gold surface, producing an absorption spectrum. The second LOS is 11.4 cm long and has a background of cool gas; it is therefore not backlit ($I_\nu(0) = 0$ for it), so it produces an emission spectrum. The third LOS is also backlit by the heated gold, and it is so short that we essentially measure just $I_\nu(0)$, i.e., the continuum from the back-lighter.

An important consequence of our design is that our absorption spectra contain a contribution from emission. Since the emission and absorption lines of sight are practically identical in length, we correct for this emission by subtracting our emission data from our absorption data. This is mainly relevant for the $H\beta$ line in our data, since it is our most strongly absorbing and emitting line. To our knowledge this is the first time such corrections have been applied to laboratory data for the purpose of line profile measurements.

2.3. Hydrodynamic effects

We believe that hydrodynamic effects, i.e., bulk motion of our plasma, are unimportant for our platform. We have used the simulation package Helios-CR [see 27] to test this hypothesis. By simulating the heating from the gold wall on the hydrogen gas in our cell, we estimate that the gas along our 10 mm LOS from the gold expands away from the wall by only ~ 1 mm in 250 ns [25]. While this is a non-zero amount, it is small and does not compromise in any way our data or our ability to analyze the data. The main consequence is that the increase in

Figure 4: The electron density versus time as measured by fits of different models to $H\beta$. The three models infer the same electron density to within 5%.

electron density seen at later times that would naively be interpreted as due to local heating may be partially due to the transport of more highly ionized plasma from closer to the gold wall into our LOS.

2.4. Strategy for testing line shape theory

The ultimate goal of this investigation is to verify or revise the current mass determinations of white dwarf stars. To do this we require final errors on the masses of $\lesssim 5\%$. This in turn requires that we know our electron density, n_e , to a precision of 5–10%. This is difficult to accomplish with plasma diagnostics such as Thomson scattering [see, e.g., 28, 29, 30].

Instead, we choose an alternate approach. Since the $H\beta$ line involves the electronic states $n = 2$ and 4, this line is much less perturbed than the lines $H\gamma$ and $H\delta$ are, which involve the $n = 5$ and 6 states, respectively.

This statement is confirmed by our fits to the data. In Figure 3, we see fits to our data of three different theoretical models: VCS, TB (Tremblay & Bergeron), and the numerical simulation method XENO [“Xenomorph”, 21, 31]. While Xenomorph fits the core of the line better, all three infer the same values of n_e and n_2 , the density of atoms in the $n = 2$ state, to within $\sim 5\%$. In addition, Figure 4 shows how the derived values of n_e evolve with time. At all but the highest densities of n_e , the theoretical line profile models that we fit to our $H\beta$ data return the same value of n_e , within the errors. Since we measure all of our lines simultaneously, we take this derived value of n_e as indicative of the plasma conditions for measured shapes and strengths of $H\gamma$ and $H\delta$ as well.

3. Preliminary Results

We are still refining our fitting and analysis methods for the data, so the fits presented here remain preliminary. We will present final reductions soon [24].

Figure 5: Fits to emission data of H γ and H δ lines taken at 40 ns, 80 ns, 120 ns, and 160 ns. While all three theories find similar values of n_e (as labeled in upper right hand of each panel), Xenomorph has a much smaller χ^2 value.

3.1. Emission line fits

In Figure 5 we present fits to our emission data spanning the region of H β and H γ . These fits include a second order polynomial to correct for possible uncertainties in instrumental response and in the continuum. They also assume a region of cool, absorbing plasma through which the radiation must pass as well as a hot region where it is emitted. Finally, prescriptions are assumed for the occupation probability of the $n = 5$ states for the various theories [32].

As expected, all three theories do a good job of fitting H β . In general, Xenomorph does better than the other theories in fitting H γ . This is most likely due to the fact that Xenomorph allows the ions to move during the calculations, whereas the other theories assume the static ion approximation.

3.2. Absorption line fits

Since our back-lighter, the heated gold, is quite bright, we are able to achieve a higher signal-to-noise ratio in our absorption measurements. This gives us the opportunity to study weaker lines, such as H δ .

In Figure 6 we present absorption data spanning the H γ and H δ lines. The theoretical curves are not simultaneous fits to

both lines. Rather, we have fit the H γ line and used the n_e and n_2 values thus obtained to calculate the expected shape of the H δ line, for the different indicated theories. The open diamonds show the absolute transmission, and the filled diamonds show the line transmission. All fits are to the line transmission data. We see that all theories are able to provide a good fit to H γ but are less successful at reproducing H δ . In addition, there is no clear winner among the theories. This was not the situation for H β in absorption (see Figure 3) or H β and H γ in emission (see Figure 5), for which Xenomorph consistently produced the best or close to the best fits. We are currently examining possible causes of this apparent inconsistency.

4. Future Directions

4.1. Occupation probabilities

When submerged within an electric microfield distribution the ionization energy of atoms in a plasma decreases. This effect, known as the lowering of the ionization potential or ionization potential depression [34, 35], can manifest as the probability that an atom exists in some state relative to that when the

Figure 6: Measured H γ and H δ line transmission (filled diamonds) and absolute transmission (open diamonds) from the first six 10-ns line-outs from experiment z2553. The theoretical curves are derived from a fit of the H γ line only, and the values of n_e and n_2 thus obtained are used to calculate the shape of the H δ line, with the following color scheme: VCS (red), VCS with the ad hoc modification from Bergeron [33, pink], TB (blue), and Xenomorph (green) line profiles. We print the corresponding χ^2_{red} values for all line profile fits and n_e from the Xenomorph fit.

Figure 7: Emission data taken at the high electron density of $n_e = 8.9 \times 10^{17} \text{ e/cm}^3$. The wavelength shift of the H γ line is quite apparent here, as continuum lowering preferentially removes the red side of the line. We note that H δ has effectively vanished at this density.

atom is surrounded by non-interacting particles, i.e., the occupation probability [see 17].

An unanticipated outcome of our experiment is that we believe we have a platform that is well suited to testing and measuring the occupation probabilities of different atomic levels [25]. This is because our experiment measures multiple absorption lines that share the same lower level population, $n = 2$. If we denote the occupation probability (for a given n_e) of the state n as w_n , then the strength of H β will be proportional to w_4 and that of H γ to w_5 . Since the oscillator strengths of these two lines are known, the measured ratio of the strengths of these lines can be turned into a measurement of the ratio w_5/w_4 .

Our experiment permits us access to densities approximately 10 times the upper limit that Wiese et al. [11] were able to reach. The physical effects just mentioned become more important as the density is increased. In Figure 7 we show an emission spectrum of such high density data ($n_e = 8.9 \times 10^{17} \text{ e/cm}^3$). First, we note that H γ is noticeably blue shifted. This is due to continuum lowering preferentially removing the red side of the line. Second, we see that H δ has effectively vanished. In the occupation probability formalism we would say that this implies that $w_6 \simeq 0$.

4.2. He, C, and O

An additional future direction for our experiment involves measurements of chemical elements other than hydrogen [36]. The second-most common “flavor” of white dwarf has nearly pure helium at its surface, so this is an obvious choice. In addition, helium is naturally in a gaseous state so our basic gas cell design should still be viable. Finally, white dwarfs with predominantly carbon or carbon/oxygen atmospheres have been discovered [37]; these would also be accessible through gases such as CO₂.

4.3. Magnetic fields

Besides the Stark-broadening of lines in white dwarfs, the next most common broadening mechanism is a magnetic field [38]. Estimates are that 5–10% of all white dwarfs are magnetic [$B \gtrsim 1 \text{ MG}$, 39]. However, many more probably have smaller magnetic fields that act to broaden their spectral lines in some fashion. On a time scale of 2–3 years the Z machine at Sandia may be able to field experiments having magnetic fields of 0.5–1 MG. This will open up a new parameter space of measurements in a domain that until now has been almost exclusively theoretical [40].

5. Conclusions

The White Dwarf Photosphere Experiment has evolved into a unique platform for simultaneously measuring emission, absorption, and back-lighter continua spectra of plasmas with WD photospheric compositions and conditions ($T_e \sim 1 \text{ eV}$, $n_e \sim 10^{16}–10^{18} \text{ e/cm}^3$). Our current experiments involve line profile measurements of hydrogen, 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. We reach significantly higher densities than the landmark studies of Wiese et al. (1972), allowing us to test not only line broadening theories but also atomic physics such as the occupation formalism of Hummer & Mihalas [17]. We believe this platform will be productive for years to come.

Acknowledgments

We thank P.-E. Tremblay for providing tables of Stark-broadened hydrogen lines for use in line profile fitting to our data. This work was performed at Sandia National Laboratories and is supported by the Laboratory Directed Research and Development program. We thank the Z dynamic hohlraum, accelerator, diagnostics, materials processing, target fabrication, and wire array teams, without which we cannot run our experiments. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000. This work has made use of NASA’s Astrophysics Data System Bibliographic Services. R.E.F. acknowledges support of the National Physical Science Consortium, T.A.G. acknowledges support from the National Science Foundation Graduate Research Fellowship Program under grant DGE-1110007, and R.E.F., T.A.G., M.H.M., and D.E.W. gratefully acknowledge support of the Norman Hackerman Advanced Research Program under grant 003658-0252-2009 and the Department of Energy under grant DE-SC0010623.

- [1] P. Bergeron, R. A. Saffer, J. Liebert, A spectroscopic determination of the mass distribution of DA white dwarfs, *ApJ* 394 (1992) 228, doi:10.1086/171575.
- [2] J. Liebert, P. Bergeron, J. B. Holberg, The Formation Rate and Mass and Luminosity Functions of DA White Dwarfs from the Palomar Green Survey, *ApJS* 156 (2005) 47–68, doi:10.1086/425738.

- [3] S. O. Kepler, S. J. Kleinman, A. Nitta, D. Koester, B. G. Castanheira, O. Giovannini, A. F. M. Costa, L. Althaus, White dwarf mass distribution in the SDSS, *MNRAS* 375 (2007) 1315, doi:10.1111/j.1365-2966.2006.11388.x.
- [4] D. Koester, B. Voss, R. Napiwotzki, N. Christlieb, D. Homeier, T. Lisker, D. Reimers, U. Heber, High-resolution UVES/VLT spectra of white dwarfs observed for the ESO SN Ia Progenitor Survey. III. DA white dwarfs, *A&A* 505 (2009) 441–462, doi:DOI: 10.1051/0004-6361/200912531.
- [5] B. G. Castanheira, D. E. Winget, K. Williams, M. H. Montgomery, R. E. Falcon, J. J. Hermes, White Dwarfs in the HET Dark Energy Experiment, in: K. Werner & T. Rauch (Ed.), *American Institute of Physics Conference Series*, vol. 1273 of *American Institute of Physics Conference Series*, 160, doi:10.1063/1.3527795, 2010.
- [6] S. J. Kleinman, S. O. Kepler, D. Koester, I. Pelisoli, V. Peçanha, A. Nitta, J. E. S. Costa, J. Krzesinski, P. Dufour, F.-R. Lachapelle, P. Bergeron, C.-W. Yip, H. C. Harris, D. J. Eisenstein, L. Althaus, A. Córscico, SDSS DR7 White Dwarf Catalog, *ApJS* 204 5, doi:10.1088/0067-0049/204/1/5.
- [7] S. O. Kepler, I. Pelisoli, D. Koester, G. Ourique, S. J. Kleinman, A. D. Romero, A. Nitta, D. J. Eisenstein, J. E. S. Costa, B. Külebi, S. Jordan, P. Dufour, P. Giommi, A. Rebassa-Mansergas, New white dwarf stars in the Sloan Digital Sky Survey Data Release 10, *MNRAS* 446 (2015) 4078, doi:10.1093/mnras/stu2388.
- [8] D. E. Winget, C. J. Hansen, J. Liebert, H. M. van Horn, G. Fontaine, R. E. Nather, S. O. Kepler, D. Q. Lamb, An independent method for determining the age of the universe, *ApJ* 315 (1987) L77, doi:10.1086/184864.
- [9] K. A. Williams, M. Bolte, D. Koester, Probing the Lower Mass Limit for Supernova Progenitors and the High-Mass End of the Initial-Final Mass Relation from White Dwarfs in the Open Cluster M35 (NGC 2168), *ApJ* 693 (2009) 355, doi:10.1088/0004-637X/693/1/355.
- [10] A. Bischoff-Kim, M. H. Montgomery, D. E. Winget, Fine Grid Astero-seismology of G117-B15A and R548, *ApJ* 675 (2008) 1505–1511, doi:10.1086/527287.
- [11] W. L. Wiese, D. E. Kelleher, D. R. Paquette, Detailed Study of the Stark Broadening of Balmer Lines in a High-Density Plasma, *Phys. Rev. A* 6 (1972) 1132, doi:10.1103/PhysRevA.6.1132.
- [12] C. R. Vidal, J. Cooper, E. W. Smith, Hydrogen Stark-Broadening Tables, *ApJS* 25 (1973) 37, doi:10.1086/190264.
- [13] E. W. Smith, J. Cooper, C. R. Vidal, Unified Classical-Path Treatment of Stark Broadening in Plasmas, *Physical Review* 185 (1969) 140–151, doi:10.1103/PhysRev.185.140.
- [14] T. Schöning, Ion-dynamical effects in the Stark broadening of H I and He II lines and the implications for high resolution spectroscopy, *A&A* 282 (1994) 994–998.
- [15] R. Napiwotzki, T. Rauch, The Balmer line problem of hot stars and the impact of ion-dynamical effects on the Stark broadening of H I and He II lines, *A&A* 285 (1994) 603–608.
- [16] P. Tremblay, P. Bergeron, Spectroscopic Analysis of DA White Dwarfs: Stark Broadening of Hydrogen Lines Including Nonideal Effects, *ApJ* 696 (2009) 1755, doi:10.1088/0004-637X/696/2/1755.
- [17] D. G. Hummer, D. Mihalas, The equation of state for stellar envelopes. I - an occupation probability formalism for the truncation of internal partition functions, *ApJ* 331 (1988) 794, doi:10.1086/166600.
- [18] R. Napiwotzki, N. Christlieb, H. Drechsel, H.-J. Hagen, U. Heber, D. Homeier, C. Karl, D. Koester, B. Leibundgut, T. R. Marsh, S. Moehler, G. Nelemans, E.-M. Pauli, D. Reimers, A. Renzini, L. Yungelson, SPY - the ESO Supernovae type Ia Progenitor survey, *The Messenger* 112 (2003) 25.
- [19] R. E. Falcon, D. E. Winget, M. H. Montgomery, K. A. Williams, A Gravitational Redshift Determination of the Mean Mass of White Dwarfs. DA Stars, *ApJ* 712 (2010) 585, doi:10.1088/0004-637X/712/1/585.
- [20] M. A. Gigosios, V. Cardeñoso, New plasma diagnosis tables of hydrogen Stark broadening including ion dynamics, *Journal of Physics B Atomic Molecular Physics* 29 (1996) 4795, doi:10.1088/0953-4075/29/20/029.
- [21] T. A. Gomez, Examining Line Broadening Approximations using Xenomorph: A Simulation Line Broadening Program, Master's thesis, The University of Texas at Austin, 2013.
- [22] M. G. Santos, S. O. Kepler, Theoretical study of the line profiles of the hydrogen perturbed by collisions with protons, *MNRAS* 423 (2012) 68, doi:10.1111/j.1365-2966.2012.20631.x.
- [23] G. A. Rochau, J. E. Bailey, R. E. Falcon, G. P. Loisel, T. Nagayama, R. C. Mancini, I. Hall, D. E. Winget, M. H. Montgomery, D. A. Liedahl, ZAPP: The Z Astrophysical Plasma Properties collaboration, *Physics of Plasmas* 21 (5) 056308, doi:10.1063/1.4875330.
- [24] R. E. Falcon, G. A. Rochau, J. E. Bailey, T. A. Gomez, M. H. Montgomery, D. E. Winget, T. Nagayama, Laboratory Measurements of White Dwarf Photospheric Spectral Lines: H β , in preparation.
- [25] R. E. Falcon, Creating and Measuring White Dwarf Photospheres in a Terrestrial Laboratory, Ph.D. thesis, The University of Texas at Austin, 2014.
- [26] D. Mihalas, *Stellar atmospheres* /2nd edition/, 1978.
- [27] J. J. Macfarlane, I. E. Golovkin, P. R. Woodruff, HELIOS-CR A 1-D radiation-magnetohydrodynamics code with inline atomic kinetics modeling, *J. Quant. Spec. Radiat. Transf.* 99 (2006) 381, doi:10.1016/j.jqsrt.2005.05.031.
- [28] A. Gawron, S. Maurmann, F. Böttcher, A. Meckler, H.-J. Kunze, HeII P_{α} Stark broadening and intensity ratio of CIV and CIII lines calibrated with Thomson scattering for high-density plasma diagnostics, *Phys. Rev. A* 38 (1988) 4737–4742, doi:10.1103/PhysRevA.38.4737.
- [29] A. J. Harvey-Thompson, S. V. Lebedev, S. Patankar, S. N. Bland, G. Burdiak, J. P. Chittenden, A. Colaitis, P. De Grouchy, H. W. Doyle, G. N. Hall, E. Khoory, M. Hohenberger, L. Pickworth, F. Suzuki-Vidal, R. A. Smith, J. Skidmore, L. Suttle, G. F. Swadling, Optical Thomson Scattering Measurements of Plasma Parameters in the Ablation Stage of Wire Array Z Pinches, *Physical Review Letters* 108 (14) 145002, doi:10.1103/PhysRevLett.108.145002.
- [30] A. J. Harvey-Thompson, S. V. Lebedev, S. Patankar, S. N. Bland, G. Burdiak, J. P. Chittenden, A. Colaitis, P. De Grouchy, G. N. Hall, E. Khoory, M. Hohenberger, L. Pickworth, F. Suzuki-Vidal, R. A. Smith, J. Skidmore, L. Suttle, G. F. Swadling, Optical Thomson scattering measurements of cylindrical wire array parameters, *Physics of Plasmas* 19 (5) (2012) 056303, doi:10.1063/1.3694671.
- [31] T. A. Gomez, R. C. Mancini, M. H. Montgomery, D. E. Winget, High Density Hydrogen Balmer Opacities I: Line Shapes, in preparation.
- [32] M. J. Seaton, Atomic data for opacity calculations. XIII - Line profiles for transitions in hydrogenic ions, *Journal of Physics B Atomic Molecular Physics* 23 (1990) 3255–3296, doi:10.1088/0953-4075/23/19/012.
- [33] P. Bergeron, Stark broadening in white dwarf atmospheres, in: M. A. Barstow (Ed.), *NATO Advanced Science Institutes (ASI) Series C*, vol. 403 of *NATO Advanced Science Institutes (ASI) Series C*, 267, 1993.
- [34] G. Ecker, W. Kröll, Lowering of the Ionization Energy for a Plasma in Thermodynamic Equilibrium, *Physics of Fluids* 6 (1963) 62–69, doi:10.1063/1.1724509.
- [35] J. C. Stewart, K. D. Pyatt, Jr., Lowering of Ionization Potentials in Plasmas, *ApJ* 144 (1966) 1203, doi:10.1086/148714.
- [36] R. E. Falcon, G. A. Rochau, J. E. Bailey, J. L. Ellis, A. L. Carlson, T. A. Gomez, M. H. Montgomery, D. E. Winget, E. Y. Chen, M. R. Gomez, T. J. Nash, An experimental platform for creating white dwarf photospheres in the laboratory, *High Energy Density Physics* 9 (2013) 82–90, doi:10.1016/j.hedp.2012.10.005.
- [37] P. Dufour, J. Liebert, G. Fontaine, N. Behara, White dwarf stars with carbon atmospheres, *Nature* 450 (2007) 522, doi:10.1038/nature06318.
- [38] S. O. Kepler, S. J. Kleinman, I. Pelisoli, V. Peçanha, M. Diaz, D. Koester, B. G. Castanheira, A. Nitta, Magnetic White Dwarfs in the SDSS and Estimating the Mean Mass of Normal DA and DB WDs, in: K. Werner & T. Rauch (Ed.), *American Institute of Physics Conference Series*, vol. 1273 of *American Institute of Physics Conference Series*, 19, doi:10.1063/1.3527803, 2010.
- [39] S. Jordan, R. Aznar Cuadrado, R. Napiwotzki, H. M. Schmid, S. K. Solanki, The fraction of DA white dwarfs with kilo-Gauss magnetic fields, *A&A* 462 (2007) 1097–1101, doi:10.1051/0004-6361:20066163.
- [40] C. Schimeczek, G. Wunner, Atomic Data for the Spectral Analysis of Magnetic DA White Dwarfs in the SDSS, *ApJS* 212 26, doi:10.1088/0067-0049/212/2/26.