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The Wootton Center for Astrophysical Plasma Properties: First Results for Helium

M. H. Montgomery[1], D. E. Winget[1], M.-A. Schaeuble[2], B. H. Dunlap[1], and J. T. Fuchs[3]

[1]Department of Astronomy and McDonald Observatory
University of Texas, Austin, Texas 78712, USA
email: mikemon@astro.as.utexas.edu, dew@astro.as.utexas.edu, bhdunlap@utexas.edu

[2]Sandia National Laboratories, Albuquerque, New Mexico 87123, USA
email: mschaeu@sandia.gov

[3]Department of Physics, Texas Lutheran University, Seguin, Texas 78155, USA
email: jfuchs@tlu.edu

Abstract. The Wootton Center for Astrophysical Plasma Properties (WCAPP) is a new center focusing on the spectroscopic properties of stars and accretion disks using "at-parameter" experiments. Currently, these experiments use the X-ray output of the Z machine at Sandia National Laboratories — the largest X-ray source in the world — to heat plasmas to the same conditions (temperature, density, and radiation environment) as those observed in astronomical objects. The experiments include measuring (1) density-dependent opacities of iron-peak elements at solar interior conditions, (2) spectral lines of low-Z elements at white dwarf photospheric conditions, (3) atomic population kinetics of neon in a radiation-dominated environment, and (4) resonant Auger destruction (RAD) of silicon at conditions found in accretion disks around supermassive black holes. In particular, we report on recent results of our experiments involving helium at white dwarf photospheric conditions. We present results showing disagreement between inferred electron densities using the Hβ line and the He I 5876 Å line, most likely indicating incompleteness in our modeling of this helium line.

Keywords. atomic data, atomic processes, methods: laboratory

1. Astrophysical Context

White dwarf (WD) stars come in two main flavors. The first, known as "DAs", have hydrogen-dominated atmospheres, and comprise approximately 75–80% of all known WDs. The second, the "DBs", have helium-dominated atmospheres, and constitute 15–20% of the WDs. The DAs are believed to the natural result of late stages of stellar evolution in which the stars with initial masses less than $\sim$ 8–10 $M_{\odot}$ evolve off the main sequence, pass through the giant phase, and lose mass. The resulting electron-degenerate object is the WD. Of course, interacting binary evolution is also believed to contribute to the production of some of these WDs, but this has not been studied in detail.

The evolutionary origin of DB WDs is currently unknown. Since the paper of Fontaine & Wesemael (1987), the prevailing view in the community has been that DAs and DBs share the same evolutionary origin. The theory presented in that paper is based on the discovery of so-called PG 1159 stars in the Palomar-Green survey (Green et al. 1986). Such stellar objects are almost completely devoid of hydrogen and mainly show He and C in their atmospheres (e.g. Reindl et al. 2015). They also have much higher temperatures than standard WDs (e.g. Werner et al. 1991, 1996), indicating that they could potentially represent evolutionary progenitors of hydrogen deficient WDs (e.g. Hügelmeyer et al. 2006; Reindl et al. 2015).

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The explanation of the origin DB WDs from PG 1159 stars is usually tightly tied to observational constraints. The hottest known WDs all have hydrogen-dominated atmospheres and start to appear at a $T_{\rm eff}$ of ∼80,000 K (e.g. Barstow et al. 2014). Fontaine & Wesemael (1987) explain this through gravitational settling: the small amounts of hydrogen present in the atmospheres of PG 1159 stars float to the top, while gravity pulls the heavier elements such as helium or carbon towards the bottom. The resulting PG 1159 star then enters the WD evolutionary track as a DA (Liebert et al. 1987). After cooling to a $T_{\rm eff}$ of ∼30,000 K, convection in the atmosphere will be significant enough to mix the outer hydrogen layer with the much more massive helium layer. A DB WD has thus been born. This final convection step is included since from an atomic physics point of view, helium lines in the atmospheres of WDs could be excited at a temperature of ∼45,000 K. A paucity of observed DB WDs in the temperature range from ∼45,000 K to ∼30,000 K necessitates the incorporation of this effect (Fontaine & Wesemael 1987).

For this proposed DB evolutionary channel to work correctly, the PG 1159 hydrogen layer mass has to adhere to very strict limits. First, its mass must be high enough to allow for the appearance of hydrogen dominated WDs at temperatures of ∼80,000 K. Second, the total mass of hydrogen also has to be low enough to enable convective mixing of the hydrogen and helium layers to produce a DB WD at ∼30,000 K (Beauchamp 1995). Third, unity optical depth has to be reached in this hydrogen layer between WD surface temperatures of ∼30,000 K and ∼80,000 K, further constraining its physical properties. This last condition ensures that the WD will appear to be a DA in that surface temperature range. Simulations show that all of the above hydrogen layer restrictions are only met if the hydrogen mass in WDs and PG 1159 stars is $\sim 10^{-15}$ $M_\odot$ (Eisenstein et al. 2006).

Nather et al. (1981) present another DB evolutionary channel. The authors describe the interacting binary system G61-29. Spectroscopic data collected on that systems leads Nather et al. (1981) to conclude that the matter being transferred between the two stellar systems is almost pure helium. Orbital period measurements of G61-29 reveal that the two member stars have a very high mass ratio. Since G61-29 is not a known X-ray source, the higher-mass member of this binary system cannot be a neutron star or black hole. It therefore must be a WD. Orbital dynamics dictate that the lower-mass member of G61-29 has to be either a ~ 1 $M_\odot$ helium-burning star or a ~ 0.02 $M_\odot$ WD. The measured absolute visual magnitude of the system is too low for a helium-burning star, indicating that the lower-mass member of G61-29 also has to be a helium WD. Nather et al. (1981) propose that the mass transfer between the two WDs will never cease leading the member stars to merge into a single stellar object, which would be a DB. It is unclear what the mass of this single DB WD would be, but it is likely that the mean mass of the DB population created under such circumstances would be dissimilar from that of the DAs.

2. Mass Determination

From the above discussion, we see that the origin of the DBs is far from settled. A key datum in this search is the average mass of the DBs, and whether it departs significantly from that of the DAs. Thus, determining the mass of the DBs is an important part of this solution.

There are two main ways in which WD masses can be determined. The first method is spectroscopic, in which the widths of the lines in an observed spectrum of the star are fit with a model atmosphere code. This code contains a model of how the lines are broadened depending on the temperature and density of their plasma environment, and

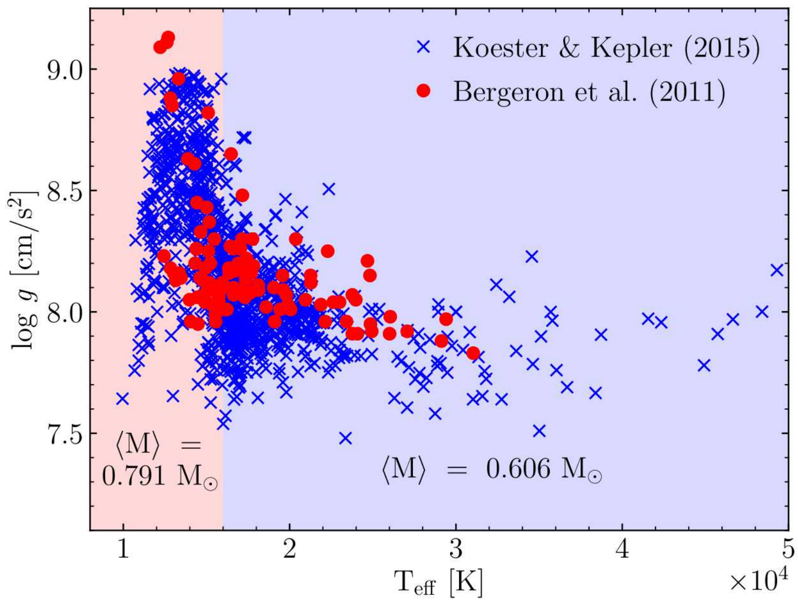

Figure 1. Comparison of spectroscopic DB results from Bergeron et al. (2011) and Koester & Kepler (2015). The sharp upturn in log g (mass) below $T_{\rm eff}$ ~ 16,000 K is likely unphysical.

this allows us to determine the $T_{\rm eff}$ and log g associated with the star. Of course, this assumes that our model for the broadening of the lines adequately describes this process.

Another powerful approach for extracting WD masses is called the gravitational redshift (GR) method. This technique relies on the principles of general relativity. Due to the large gravitational field of a WD, any photon leaving its surface will lose energy. This energy loss manifests itself in a ~1 Å shift of WD spectral lines (e.g., Adams 1925; Greenstein & Trimble 1967; Falcon et al. 2010, 2012; Barstow et al. 2005). The following equation relates this shift to the WD mass:

$$\frac{\Delta\lambda}{\lambda} = \frac{GM}{Rc^2}. \tag{2.1}$$

Since WDs are supported by electron degeneracy, there is a fairly narrow theoretical mapping from their masses to their radii. Thus, this equation can be used to find the total WD mass. Of course, other effects such as the Doppler shift dominate the GR. In the case of a very select group of stars (e.g. 40 Eri, and Sirius B) the velocity shift can be accounted for through astrometric measurements (Popper 1954; Barstow et al. 2005, 2017). A different approach must be employed account for the Doppler shift of spectral lines observed in all other WDs. In addition, for the DBs the spectral lines to be measured are those of helium, and for these, and in particular the 5876 Å line, the unknown pressure shifts of the lines introduce large uncertainties.

Finally, the Gaia satellite mission (e.g. Gaia Collaboration et al. 2016) has produced and will continue to produce distance estimates for large numbers of white dwarf stars. Coupled with photometric observations plus mass-radius models, these will yield mass estimates for these WDs (Bergeron et al. 2019). However, the precision of these estimates for individual stars will always be below those possible from high signal-to-noise spectroscopic observations, reinforcing our need for accurate atomic physics as input for spectroscopic models of these stars.

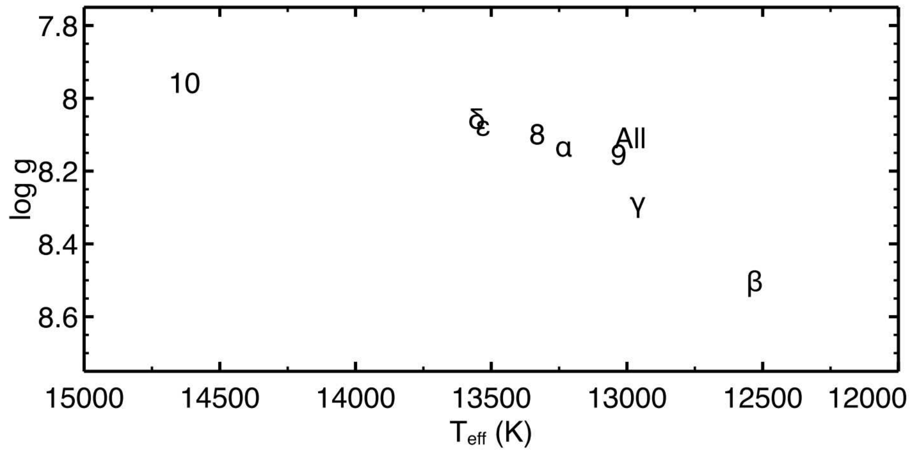

Figure 2. Each Balmer line gives a unique set of atmospheric parameters. For this observation of the DA WD L 19-2, we mark the solution from each line by its transition name, showing Hα through H 10. The weighted solution obtained by using all the lines is marked "All" (figure taken from Fuchs 2017).

3. Astrophysical Problems

Figure 1 shows the results of two different spectroscopic analyses of DB WDs (Bergeron et al. 2011; Koester & Kepler 2015). The most striking feature of this figure is the sharp upturn at $T_{\rm eff} \sim 16{,}000$ K. The stars are not thought to increase in mass as they cool, so this upturn is believed to be unphysical. Broadening of the lines by neutral helium atoms becomes important at these temperatures, so it is natural to question whether inadequacies in the theoretical prescription for this broadening are at least partially responsible for this upturn.

We note that the situation is also not rosy for the case of DA (hydrogen atmosphere) WDs. Depending on which line in the Balmer series is used for fitting, a different set of atmospheric parameters may be derived for the same star (Fuchs 2017). This is demonstrated graphically in Figure 2, which shows the result of independently fitting lines in the Balmer series from Hα to H 10. Ideally, we would like to obtain similar log g and $T_{\rm eff}$ values for each spectral line.

4. Laboratory Measurements

Since the astrophysical mass measurements are only as good as the input atomic physics in the models, one of our experimental efforts on the Z machine at Sandia National Laboratories (SNL) is focused on measuring the width and pressure shift of the helium 5876 Å line. These efforts have been led by M.-A. Schaeuble, a former graduate student at UT-Austin (Schaeuble 2018) and a current staff member at SNL.

The White Dwarf Photosphere Experiment (WDPE) is an experiment on the Z machine at SNL focused on measuring the spectral lines of low atomic number elements at conditions relevant for the photospheres of WD stars. It was one of the original experiments developed as part of the Z Astrophysical Plasma Properties (ZAPP) collaboration (see Rochau et al. 2014)

To date, we have concentrated on the spectral lines of hydrogen and helium, although we have plans to examine carbon in the near future. We note that a unique feature of our design is that we are able to simultaneously measure absorption, emission, and the

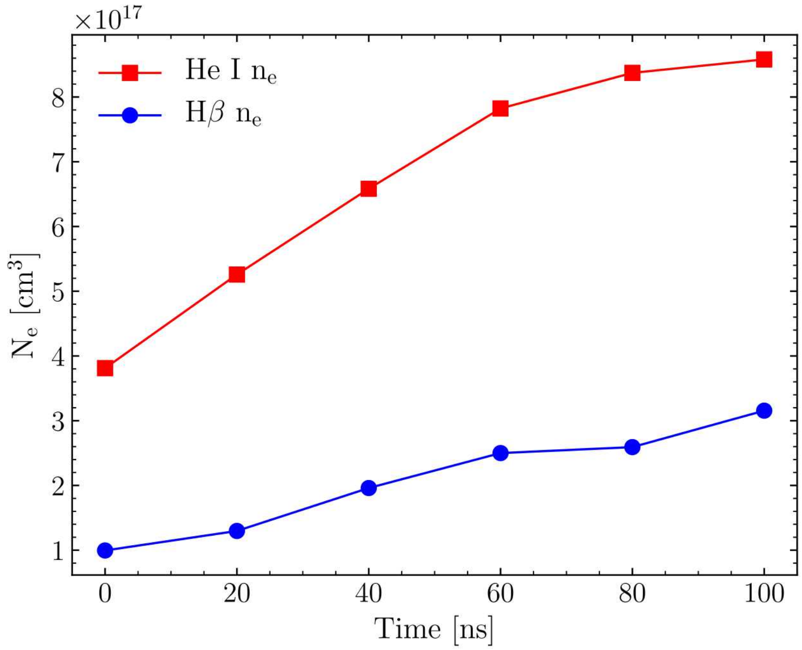

Figure 3. Electron densities inferred from He I 5875.6 Å and Hβ. Our platform was developed around Hβ and we are therefore confident in the electron densities inferred by that line. The electron density diagnostics provided by the He I spectral lines are suspect due to lack of experimental verification of the Deridder & van Renspergen (1976) neutral broadening calculations.

continuum used for backlighting the absorption measurements. For a detailed description of our experiment and gas cell design we refer the reader to Falcon et al. (2013).

Here we report on a discrepancy between the plasma conditions inferred from hydrogen and helium lines simultaneously measured in the same plasma. Since the WDPE has been developed and tested using the Hβ line, we are confident in the electron densities inferred from it. In particular, all the theoretical models for line broadening agree in this parameter domain, so the derived values of n_e, the free electron density, are virtually model independent (Falcon et al. 2015).

In Figure 3, we show the electron densities derived from Hβ and the helium 5876 Å line. We see that the derived electron densities differ by a factor of ~ 3.5, and that this difference is maintained over a range of electron densities spanning a factor of 3. The helium line width diagnostic depends on the neutral broadening calculations of Deridder & van Renspergen (1976), which are the only ones available; they have never been experimentally tested in this regime, yet they are used in all WD model atmosphere codes. This discrepancy highlights the need for a better theoretical description of neutral broadening, and also suggests that the (likely unphysical) upturn in log g observed in Figure 1 is due to the use of an inaccurate neutral broadening model in the model atmosphere calculations.

5. Futures

The current focus for the WDPE is analyzing and publishing our results on the broadening and pressure shifts of the helium 5876 Å line. We are also working on an analysis comparing the Hβ and Hγ lines, both in absorption and emission. Finally, on a one-to two-year time scale we will begin measurements and analysis of select carbon lines. The ultimate goal of these investigations is to improve the atomic physics in the model atmospheres of WDs, so that the full astrophysical potential of the white dwarf stars can be realized.

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