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The white dwarf mass-radius relation with Gaia, Hubble and FUSE

Simon R. G. Joyce[1], Martin A. Barstow[1], Sarah L. Casewell[1], Jay B. Holberg[2] and Howard E. Bond[3]

[1]Dept. of Physics & Astronomy, University of Leicester,
University Road, Leicester, LE1 7RH
email: srgj1@le.ac.uk mab@leicester.ac.uk slc25@le.ac.uk

[2]University of Arizona, LPL,
Tucson, AZ, USA
email: holberg@argus.lpl.arizona.edu

[3]Pennsylvania State University, University Park, PA, USA
email: bond@stsci.edu

Abstract. White dwarfs are becoming useful tools for many areas of astronomy. They can be used as accurate chronometers over Gyr timescales. They are also clues to the history of star formation in our galaxy. Many of these studies require accurate estimates of the mass of the white dwarf. The theoretical mass-radius relation is often invoked to provide these mass estimates. While the theoretical mass-radius relation is well developed, observational tests of this relation show a much larger scatter in the results than expected. High precision observational tests to confirm this relation are required. Gaia is providing distance measurements which will remove one of the main source of uncertainty affecting most previous observations. We combine Gaia distances with spectra from the Hubble and FUSE satelites to make precise tests of the white dwarf mass-radius relation.

Keywords. stars : distances, stars : white dwarfs, stars : fundamental parameters : masses : radii

1. Introduction

White dwarfs (WDs) are the remains of stars below ~ 8 M$_\odot$ which have ended their nuclear burning main sequence lifetime. They are no longer generating heat so they slowly cool down from temperatures of over 100,000 K to a few thousand Kelvin, and will eventually fade into the hypothetical black dwarfs. The study of WDs can lead to a greater understanding of the stellar population throughout the history of our galaxy. For example, the mass of the WD we see today is related to the mass of its progenitor star by the initial-final mass relation (Weidemann 2000). Also, the predictable way that WDs cool over billions of years means that if we can measure a WD's mass and temperature, we can derive its age, and by extension, the ages of associated stars (e.g. Fontaine *et al.* 2001, Oswalt 2012). In order to use WDs for such studies, we must have a reliable way of finding the mass and radius of the WD since these are the main factors that determine the rate at which it will cool down. The ammount of energy stored depends on the mass of the WD and the radius (as it relates to surface area) limits how quickly heat can be radiated away.

The key to obtaining accurate masses for WDs is the mass-radius relation (MRR) which allows us to derive the mass and radius of a WD from spectroscopic observations (Tremblay *et al.* 2017). Despite its well accepted theoretical basis, the white dwarf MRR has been difficult to test observationally due to the difficulty in making observations of sufficient precision. Studies (e.g. Holberg *et al.* 2012, Parsons *et al.* 2016) have shown that the few WDs we can measure reliably are consistent with the general form of the MRR. However, the results are not precise enough to distinguish between refinements to the MRR which take into account the finite temperature of the WD and the thickness of the surface hydrogen layer (Fontaine *et al.* 2001). A major problem has been the large uncertainty in the distances which are required input to calculations of the mass and radius. A further problem is that many targets do not have parallaxes available in the Hipparcos catalogue. Gaia DR1 has increased the number of targets for which both parallax and spectral data are available, making them suitable targets to include in this study.

We present the results of combining Gaia DR1 parallax data with optical spectroscopy from the Hubble Space Telescope (HST) and far-UV spectroscopy from FUSE which will allow us to make high precision tests of the white dwarf mass-radius relation.

2. Observational tests of the MRR

In order to test the MRR we measure the mass and radius using the spectroscopic method (Bergeron *et al.* 1992). Following this method we fit models to the Balmer and Lyman absorption lines in the WD spectrum which are caused by the thin layer of hydrogen on the surface of the WD. The extreme gravity of WDs causes pressure broadening of the absorption lines. The surface gravity ($log\ g$) and temperature (T_{eff}) are obtained from the model. The data are flux calibrated so the model normalisation can be combined with the distance from Gaia to calculate the radius of the WD (eqn 1).

$$R = \sqrt{D^2 \times norm} \div R_{\odot} \tag{2.1}$$

Once the radius is known, we combine it with log g to calculate the mass (eqn 2). This method is dependent on knowing the distance to the WD unlike the usual method of calculating the mass from log g and (eqn 2) which takes the ratio (M/R) from the MRR assuming it is correct.

$$M = \frac{gR^2}{G} \tag{2.2}$$

The Gaia TGAS catalogue (Brown *et al.* 2016) only contains parallaxes for ∼6 WDs (Tremblay *et al.* 2017) due to the fact that most blue stars were not included. For this study, we make use of a sample of WDs which are in binaries with main sequence stars. These are known as Sirius-like systems. By taking the parallax for the main sequence star, we can infer the distance of the WD.

One disadvantage of Sirius-like systems is that the main sequence star is much brighter than the WD and it can be difficult to obtain a spectrum of the WD which is not contaminated by scattered light from the primary star. Many of these systems are too close to be resolved even with HST. In these situations, it is possible to obtain the spectrum of the WD in far-UV wavelengths, where it is much brighter than the main sequence star. Even for unresolved systems, we can obtain the Lyman line spectrum of the WD with little contamination from the companion star.

Our sample includes Balmer line spectra from HST and far UV (Lyman line) spectra from FUSE. In principal, the results from either set of lines should be consistent, although there is evidence that this might no be true for WDs above 50,000 K (Barstow *et al.* 2003). Several of our targets have data available for both wavelength ranges which allows us to test the validity of this assumption.

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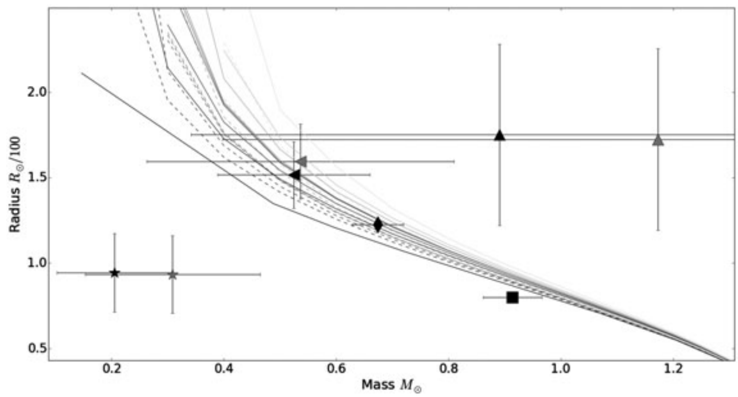

Figure 1. The mass-radius results from HST (black) and FUSE (grey) calculated using parallax data from Hipparcos compared to the theoretical mass radius relation (Fontaine *et al.*2001). The temperature ranges from zero temperature (solid black line) to 45,000 k (light grey). The symbols are Sirius B (square), HZ43 B (star), 14 Aur Cb (upright triangle), HD2133 B (left pointing triangle), HR1358 B (diamond).

3. Results

When the mass-radius values are calculated using the parallaxes avaiable from Hipparcos (van Leeuwen. 2007) there is no correlation with the mass radius relation and the error bars are too large to draw any meaningful conclusion (fig 1). In contrast, the results using the same spectra with parallaxes from Gaia show much better agreement with the MRR (fig 2).

The HST results show better agreement with the MRR than the FUSE data which appears to have a systematic offset to higher mass values. When comparing results for targets where we have both Balmer and Lyman line spectra, the mass is higher for the FUSE spectra by $\sim$0.2 $M_\odot$. Only HD2133 B has HST and FUSE mass values that are consistent with each other. In contrast to the mass estimates, the radius values are consistent for all targets when comparing Lyman and Balmer line results. This indicates that the cause of the offset is more likely due to the log g parameter found from the models rather than scatter due to the uncertainty in the parallaxes. It will require further investigation to properly understand the significance and cause of this offset.

The error bars in the mass axis have been reduced to the level where they no longer cover the full spread in theoretical models calculated for different temperatures. This raises the possibility that the data can now be used to distinguish between models with different temperature and H layer thickness.

4. Future work

The current set of results show the potential of this method and data set for testing the theoretical mass-radius relation for white dwarfs. The distance errors, which have been the main source of uncertainty in previous studies have been significantly reduced in the Gaia DR1 cataloge. Currently the average uncertainty in the distances in this sample is still 0.39 mas. We anticipate that in DR2 and beyond the parallax errors will be reduced to around 6.7 μas. In addition, distances for many more targets will be included for which we already have high quality spectra. This combination of high S/N spectra and highly accurate distance measurements will finally allow us to test the subtle variations of the MRR.

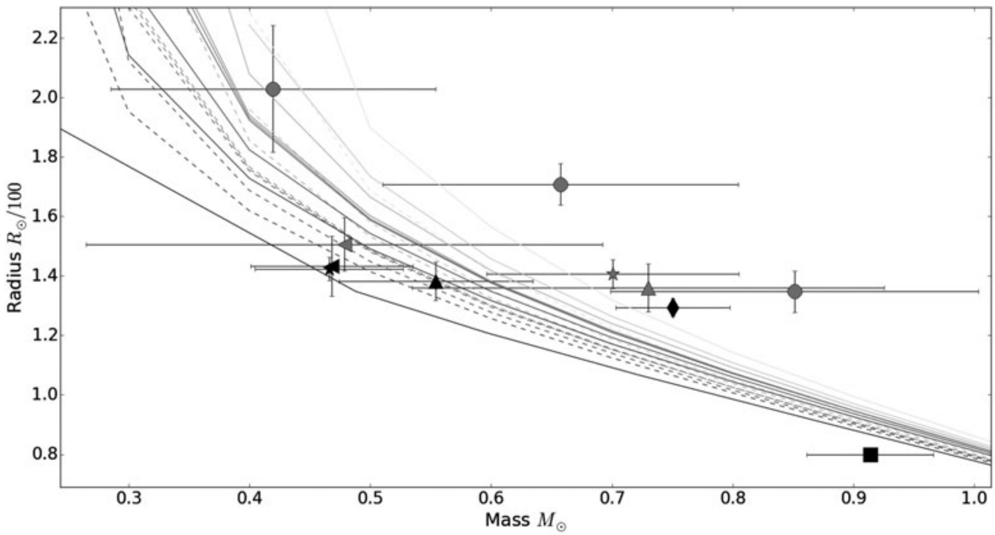

Figure 2. The mass-radius results from HST (black) and FUSE (grey) calculated using parallax data from Gaia TGAS. The symbols are the same as for fig 1. All other FUSE targets are circles.

The data are now approaching the stage where the distance will no longer be a source of significant uncertainty. This will start to uncover the effects of the other uncertainties in the data due to the stellar models used and the reliability of the fitting technique. We plan to use this set of high quality spectra to quantify these remaining sytematic effects so that they can be taken into account when future studies are undertaken which make use of spectra from thousands of white dwarfs.

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