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Gaia and white dwarf - brown dwarf binaries

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Abstract. White dwarf-brown dwarf binaries are excellent benchmark systems, as the white dwarf provides an accurate (although model dependent) age calibrator for the brown dwarf. While these systems are rare, with authors suggesting the frequency to be between 0.5 and 2 %, they are being used to provide ages for the coolest brown dwarfs (e.g. WD0806-661) and also as testbeds for irradiated atmospheres. *Gaia* is estimated to detect ~2000 of these systems using astrometry, enlarging the sample, and allowing limits to be placed on the brown dwarf desert.

Key words. stars:white dwarfs, stars:brown dwarfs

1. Introduction

Brown dwarfs (BDs) are degenerate objects and so cool and shrink as they age, creating a degeneracy between age and luminosity. A T dwarf may be old, and have cooled, passing through the spectral sequence from an L dwarf, or it may be a young, freshly formed T dwarf. This presents an inherent problem when observing brown dwarfs. We need to disentangle this degeneracy to fully understand the effect of gravity (age) and metallicity on the BD atmosphere, and to ensure that when spectral typing objects we are comparing objects of the same age.

One way of doing this is to locate a BD in a binary with a main sequence star, for which the metallicity and age can be determined. However, there is a known dearth of close BD companions to main sequence stars, known as the BD desert (Metchev & Hillenbrand 2009). There is also a potential problem, in that for the few systems that do exist, detecting the BD is challenging due to the brightness of the main sequence companion. An alternative is to move to systems where the contrast ratio is more favourable - White dwarf (WD)+ BD binaries.

WD+BD binaries are rare, which is reflected in the statistics for the evolved systems. The most detailed estimate of the statistics was performed by Steele et al. (2011) who cross-correlated the Sloan Digital Sky Survey (SDSS) DR4 and the McCook & Sion catalogue of WDs (McCook & Sion 1999) with the UKIRT Infrared Deep Sky Survey (UKIDSS) Large Area Survey to search for known WDs with an infrared excess indicative of a cool, red companion. They produced a list of 9-11 objects as candidate WD+BD systems, resulting in an unresolved binary fraction of $\geq 0.4 \pm 0.3$ per cent for WD+L dwarfs and ≥ 0.2 per cent for WD+T dwarfs. Overall, this gives a WD+BD binary fraction of $\geq 0.5 \pm 0.3$. A similar study was performed by Girven et al. (2011) who used the wider SDSS DR7 photometry to identify new WDs that showed an infrared excess in either WISE or UKIDSS. They determined a binary fraction of 2 per cent with a firm lower limit of 0.8 per cent. This lower limit is derived from systems that have spectroscopically confirmed WD primaries. Debes et al. (2011) performed a similar survey using WISE and SDSS DR7, and discovered 42 candidate WD+BD systems.Verbeek et al. (2014) used SDSS, 2MASS, UKIDSS, WISE and UVEX to identify 7 candidate systems although only one has a confirmed WD primary.

There have however, also been a number of wider systems discovered through common proper motion surveys such as LSPM 1459+0857 AB (WD+T4.5, 16500-26500 AU: Day-Jones et al. 2011), and WD0806-661AB (WD+Y?, 2500 AU: Luhman, Burgasser & Bochanski 2011), as well as resolved systems discovered using infrared excesses: PHL5038 (WD+L8, 50 AU: Steele et al. 2009) and GD165 (WD+L4, 120 AU Becklin & Zuckerman 1988).

One subset of the (as yet) unresolved candidates are post common envelope systems. These BDs began in a close (2-3 AU) orbit around a main sequence star and have survived the demise of this companion, which moved onto the red giant or asymptotic giant branch, and engulfed the BD. The BD then spiralled inwards, stopping when the outer envelope was ejected. There are 5 systems known to date: GD1400 (WD+L6, P=9.98hrs; Farihi & Christopher 2004; Burleigh et al. 2011), WD0837+185 (WD+T8, P=4.2hrs; Casewell et al. 2012), NLTT5306 (WD+L4-L7, P=101.88 min; Steele et al. 2013) and CSS21055 (Beuermann et al. 2014) which is eclipsing, but currently lacks a direct detection of the brown dwarf. These close systems are likely tidally locked, meaning they have a day- and night-side where the temperature difference may be as large as 500 K (Casewell et al., in prep), similar to the effects seen in some exoplanets. This makes them excellent testbeds for irradiated atmospheres as longwards of the *H* band, the BD flux dominates (e.g. Burleigh et al. 2006).

While *Gaia* will not measure radial velocities for WDs, it will provide proper motions and the parallaxes. Indeed, Torres et al. (2005) predict that *Gaia* will detect all disk WDs within 100 pc, half of the WDs at 300 pc and one third at 400 pc down to G <20, although the completeness is much lower for halo WDs: in total ~50 000 WDs.

2. Fundamental properties of WDs

Dupuy & Kraus (2013) describe the WD+BD binary WD0806-661 as one of the securest candidates (at the time of writing) for the coolest temperature BD, largely in part to its well defined age, highlighting the importance of an accurate age measurement.

It is however, impossible to determine the metallicity of a WD from its spectrum. This is due to the cooling processes that occur, causing heavier metals to sink to the core of the WD. These metals, may then reappear in the photosphere due to radiative levitation that occurs at $T_{\rm eff}$ > 20000 K (Barstow et al. 2014). WDs are also seen to be polluted by material that may be remnants of planetary systems (Jura, M 2006). As such, measuring metal lines in a WD spectrum, is not a reliable way of determining the progenitor metallicity. However, many WDs are found in close binaries with main sequence stars, known as Sirius like binaries. If a BD were discovered as a companion to a Sirius like binary, then the metallicity for the primary star can be used to determine the metallicity of the BD. There are 98 Sirius like systems known to date (Holberg et al. 2013), some of which are triple systems, the majority are within 20 pc, although *Gaia* is likely to discover many more.

The effective temperature ($T_{\rm eff}$) and log g are the most commonly measured parameters for WDs. They are measured using the hydrogen lines in the visible part of the spectrum with a moderate resolution spectrograph (e.g. Dobbie et al. 2006). By using a grid of model atmospheres such as those generated by TLUSTY (Hubeny 1988; Hubeny & Lanz 1995) and spectral synthesis code SYNSPEC (Hubeny & Lanz 2001), or those described in Koester (2010), it is possible measure the $T_{\rm eff}$ and log g using the hydrogen lines (e.g. Casewell et al. 2009; Dobbie et al. 2009a). If spectra are not available, it is possible to use synthetic photometry such as that in Holberg & Bergeron (2006), adjusted for the distance modulus to obtain an estimate of the $T_{\rm eff}$ and

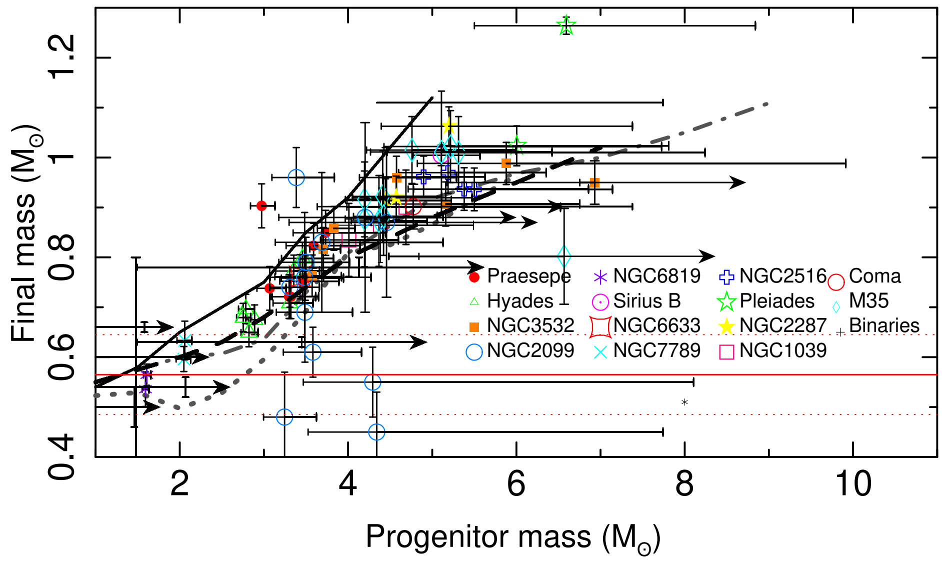

Fig. 1. Final masses versus initial masses of the available cluster and wide binaries data (Weidemann 1987, 2000; Ferrario et al. 2005; Dobbie et al. 2006; Williams & Bolte 2007; Kalirai et al. 2008; Rubin et al. 2008; Catalan et al. 2008; Casewell et al. 2009; Dobbie et al. 2009a,b). The dashed black line is the semi-empirical Weidemann (2000) IFMR, the thick solid line is the IFMR as given by the Girardi et al. (2000) models, the grey dot-dashed line is a fit to the data and the grey dotted line is the initial mass-core mass at the first thermal pulse relation from Karakas, Lattanzio & Pols (2002). The peak in the field WD mass distribution (thin solid line) and $\pm 1\sigma$ is represented by the thin dotted lines.

log g, or to generate synthetic photometry from a model grid such as Girven et al. (2011) did for their sample.

The $T_{\rm eff}$ and log g, when combined with cooling models can be used to determine the mass, radius and luminosity for the WD. Such examples of models are those by Fontaine, Brassard & Bergeron (2001); Althaus & Benvenuto (1997, 1998); Wood (1995) which contain either carbon (M< 0.5 M$_\odot$) or carbon-oxygen cores (M>0.5 M$_\odot$), and either thick or thin hydrogen atmospheres. Once the mass of the WD is known, this can be combined with an initial mass-final mass relation (IFMR: Figure 1), to determine the progenitor mass of the WD.

The semi-empirical IFMR is derived using mainly cluster WDs - these have a cooling age calculated from models, and use the fact that the cluster age is a sum of the WD cooling time and the main sequence age of the progenitor. Wide binaries (those where there has been no interactions between the WD and its main sequence companion) are also used as gyrochronology can be used to estimate the age of the main sequence star, and hence the WD total age. Some caution should be exercised however, as the high mass and low mass ends of the IFMR are not well defined - this is particularly pertinent for the close WD+BD systems, as the majority have a lower than average mass WD primary. The reason for the lack of data in the IFMR at the extremes of the mass range is that the majority of the open star clusters that are nearby are too young to contain low mass WDs, as higher mass stars evolve faster. Therefore the low mass WDs in the IFMR are those in wide binary systems (100 to 1000 AU), where the two components have evolved as single stars (Catalan et al. 2008). There are few of these binaries, as a parallax is required in order to obtain the luminosity of the companion with accuracy, and hence the age of the system, and indeed the uncertainties on the parallax dominate the errors. *Gaia* will measure the parallax of each component with much more accuracy, as well as providing proper motions and radial velocity for the stellar member of the binary. These parameters can be used to confirm that the stars are indeed co-moving, as well as decreasing the errors on the IFMR.

Combining the progenitor mass from the IFMR with models of main sequence stars such as those by Girardi et al. (2002), will then allow the main sequence lifetime of the WD progenitor to be determined, and hence the total age of the system to be calculated. Knowledge of the progenitor mass also allows us to assemble statistics on the BD desert. Comparing the statistics between known main sequence +BD and WD+BD binaries will also allow us to determine the percentage of BDs that do not survive the death of their star.

3. Conclusions: what Gaia will change

In providing parallaxes for ~50 000 WDs (Torres et al. 2005), *Gaia* will enable us to increase the accuracy of the semi-empirical IFMR. Currently, the errors are dominated by the errors on the distances to the cluster, and binary WDs used. In general, the distance to the cluster is assumed for every WD member. This is a reasonable assumption for some clusters, however for nearby clusters which occupy a large region of sky, and hence a large depth (e.g. Hyades), the same distance cannot be assumed for every WD. *Gaia* will also provide parameters for WDs in binaries with main sequence stars. It will provide excellent parallax, proper motions and radial velocities, albeit the latter for the main sequence star only, with which to identify new, and confirm known binaries. These systems are the best opportunity for constraining the low mass end of the IFMR.

Gaia will also discover new WD+BD binaries using astrometry. Using the estimated binary fractions, perhaps as many as 2000 new systems may be discovered. In many, the BD will be of a late spectral type, making the system difficult to identify by an infrared excess (e.g. Casewell et al. 2012).

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