Discovery of the first white dwarf + T dwarf binary system and the use of white dwarfs as age calibrators

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Abstract. We present the discovery of the first white dwarf + T dwarf binary system. Systems containing a white dwarf and a brown dwarf are rare but can be used to place constraints on the age of the binary, making them valuable benchmark systems. It is currently not possible to calculate brown dwarf ages from models alone and white dwarfs provide an opportunity to aid the calibration of these models. We describe our program to identify such benchmark binary systems in the latest releases of UKIDSS/SDSS and review the level of constraints currently provided by benchmark objects. Finally we describe the niche age space that white dwarf + brown dwarf binary systems can provide and look at how many more systems may be identified in future surveys, such as VISTA and WISE.

Keywords: white dwarfs, brown dwarfs, binaries,

INTRODUCTION

The identification of ultracool or brown dwarfs (BDs) as companions to white dwarf stars have the potential to be benchmark systems, whereby the white dwarf can provide an age constraint on the BD. Currently there is no unique mass-luminosity, or mass-Teff relationship for BDs, but it is instead dependent on mass and age (Allard et al. 2001), which are currently derived from model fitting. These models are very sensitive to a variety of poorly understood processes in BD atmospheres and the spectroscopic fitting of atmospheric properties is a major challenge and without well constrained atmospheric properties there is no way to accurately determine mass or age. Identifying objects where one can pin down these properties independently are thus invaluable aids for the calibration of models. In particular white dwarf primaries have the potential to provide robust ages and tight benchmark constraints. In general the best constrained ages are likely to come from higher mass white dwarfs (>0.65M⊙), which will have higher progenitor masses short main-sequence (MS) lifetimes. The ages of these systems are likely to be constrained at the 10% level (Pinfield et al. 2006). For lower masses, with more solar like progenitors the MS lifetime is more uncertain, however they can provide a hard lower limit on the age of the system.

Binary systems containing a white dwarf and a BD (which are not members of CVs),
however are observationally rare, and only a handful of such binaries have been identified, despite several searches for such systems. To date there are only five white dwarfs that have been spectroscopically confirmed to have BD companions, with spectral types later than L. These include GD 165B (L4; Zuckerman et al. 1992), GD 1400 (L6/7; Farhi et al. 2004; Dobbie et al. 2005), WD 0137 − 349 (L8; Maxted et al. 2006; Burleigh et al. 2006), PG1234+482 (L0; Steele et al. 2007; Mullally et al. 2007) and PHL 5038B (L8; Steele et al. 2009) previously the latest type BD companion to a white dwarf.

**COMMON PROPER MOTION SEARCHES OF UKIDSS T DWARFS**

We searched for candidate common proper motion companions to a sample of spectroscopically confirmed T dwarfs that were identified from the UKIDSS Large Area Survey (DR5), that had proper motion measurements (Pinfield et al. 2008 and Burningham et al. 2010). Objects from the SuperCOSMOS archive were then downloaded for an area around each T dwarf corresponding to a separation of 20,000AU at the distance of the T dwarf (estimated using the absolute magnitude-spectral type relations from Liu et al. 2006). The colours of any object that had a common proper motion (at the 2 σ level) were then assessed by comparing their colours with those expected for main-sequence stars and white dwarfs, following the approaches described in Clarke et al. (2009) and Day-Jones et al. (2008). We found only one main-sequence companion candidate was identified, Wolf 940 which had previously been identified serendipitously by Burningham et al. (2009). We also identified five candidate common proper motion companions that were consistent with the white dwarf sequence (see Fig. 1.).

The brightest of our white dwarf candidates appears in the LSPM catalogue (LSPM J1459+0851, Lepine et al. 2005) as a high proper motion object, although it has not been previously studied spectroscopically. The T dwarf associated with this object is ULAS J1459+0857, which has been spectroscopically typed as a T4.5±0.5 dwarf (Burningham et al. 2010). This pair is highlighted in Fig. 1.

**THE FIRST WHITE DWARF + T DWARF BINARY SYSTEM**

Spectroscopic observations of LSPM J1459 + 0851 were obtained with FORS2 on the Very Large Telescope. The spectra covering a range of 3300−8000Å showed a general black-body shape, consistent with a white dwarf or a very metal poor sub-dwarf (e.g. Jao et al. 2008). However the overall strength of the Hα line and the peak of the blackbody-like continuum are only consistent with a cool white dwarf (Kilic et al. 2006). We also compare LSPM J1459 + 0851 to the spectra of three other very cool, hydrogen rich (DA) white dwarfs; WD0011-134, WD 1330+015 and WD 0503-174, taken from Bergeron, Ruiz & Leggett (1992) and Bergeron, Ruiz & Leggett (1993) in Fig. 3. Although the spectra of LSPM J1459 + 0851 is noisier, it can be seen that the extent of the Hα feature is consistent with a cool, hydrogen rich white dwarf.
FIGURE 1. Left: A colour-magnitude diagram of white dwarfs from McCook & Sion (1999) with known parallax (crosses). Photometry is on the SuperCOSMOS system. Overplotted are model cooling tracks (see main text) for white dwarf masses of 0.5, 0.7 and 1.2 $M_\odot$ (dotted, dashed and dot-dashed lines respectively). Also overplotted is our white dwarf selection region (two solid lines), along with our candidate white dwarf companions (large stars). Right: A two colour diagram in SDSS colours showing populations of main-sequence stars (blue points), M dwarfs (orange triangles), white dwarfs (green asterisks) and K subgiants (red squares), with our white dwarf candidates overplotted as black stars. LSPM J1459+0851 is circled for reference.

FIGURE 2. Right: Top: Fit of the energy distribution with pure-H models. The observed $ugriz$ and $JHK$ fluxes are represented by error bars while the model fluxes averaged over the filter bandpasses are indicated by filled circles. The model monochromatic fluxes are shown by a solid line. Bottom: Normalised spectrum near H$\alpha$ with the synthetic profiles assuming a pure-H atmospheric composition with a model fit at $T_{\text{eff}}=5535 \pm 45K$ and $\log g = 8.0$. Left: Optical spectrum in the region of H$\alpha$ for the white dwarf LSPM J1459+0851. For comparison the spectra of three similar cool, hydrogen rich, magnetic white dwarfs, WD 0011-134 (B$\sim$16.7MG), WD 1330+015 (B$\sim$7.4MG) and WD 0503-174 (B$\sim$7.3MG) are also shown, with magnetic field strength decreasing from top to bottom.
Properties of the white dwarf

Properties of the white dwarf were determined using the atmospheric model codes of Bergeron et al. (Bergeron et al. 2001; Bergeron et al. 2005; Bergeron et al. 1995). We fit available photometry of the full optical (SDSS) and NIR (UKIDSS) SED for a pure-H model to determine the effective temperature of $T_{\text{eff}} = 5535 \pm 45$ K and we assume $\log g = 8.0$, which is consistent with the distance estimate of the T dwarf companion. This fit is shown in Fig. 2. The shape and weakness of the H$\alpha$ line gives a poor fit to a basic 5535 K model spectra, and we thus investigated the possibility that the white dwarf could be magnetic with the H$\alpha$ line affected by Zeeman splitting. We computed a series of synthetic spectra based on a pure-H model with the corresponding $T_{\text{eff}}$ and $\log g$, and varying $B_d$, $i$, and $\alpha_z$. The best fit came from an observed line profile with $B_d = 2.0$ MG, $i = 45^\circ$ and $\alpha_z = -0.20$. This can be seen in Fig 2 and is directly compared to the same feature in other cool white dwarfs of similar magnetic field strengths.

Properties of the binary system

We calculated the cooling age of the white dwarf, firstly assuming a simple, non-magnetic case for a $T_{\text{eff}}$ and $\log g$ of 5535 K and 8.0, for which we calculate a mass of 0.585 M$\odot$ (Fontaine et al. 2001). The corresponding cooling age of a 0.585 M$\odot$ white dwarf was then calculated as 3 Gyr using the isochrones of Fontaine et al. (2001). The total age of the white dwarf comprises of both the cooling time and its progenitor lifetime on the MS. The MS lifetime was accessed using the Initial-final mass relations of Ferrario et al. (2005), Catálan et al. (2008) and Kalirai et al. (2008) to estimate a likely, initial-mass constraint for the MS progenitor star of 1.50-1.75 M$\odot$. We then used the tracks of Lachaume et al. (1999) to estimate the MS lifetime of such masses as 1.8-3.0 Gyr. However as the white dwarf has a strong magnetic field one must be cautious as the origins of such strong magnetic fields is unclear. Favoured scenarios include the evolution of a single, initially highly magnetic Ap or Bp star, which maintains its magnetic field through flux conservation. The other most favoured scenario involves the merger of two stellar cores during the common envelope phase. Also there is evidence that magnetic white dwarfs have higher masses (Liebert et al. 1988). If this were the case for LSPM J1459+0851 then the cooling time would be longer (6 Gyr) and the MS progenitor would be around 3.5 M$\odot$ (Catálan et al. 2008), such that the MS lifetime would be much shorter, in the region of 0.3 Gyr. However as we cannot ascertain more accurately the mass of the white dwarf or know which mechanism is responsible for its strong magnetic field (which in any case would only result in older ages) we choose to adopt a minimum age of 4.8 Gyr.

A BENCHMARK SYSTEM

As the age of the system is constrained by the white dwarf then the BD component can be considered a benchmark object. Properties of ULAS J1459+0857 are described fully in Burningham et al. (2010) and Day-Jones et al. (2010). We used the age constraint
FIGURE 3. Left: Spectral model comparisons to ULAS J1459+0857 (black solid line) for $T_{\text{eff}}=1200$ K and $[\text{M/H}]=+0.3, 0.0$ and $-0.5$, from top to bottom, with $\log g = 5.0, 5.25$ and 5.5 as a long red dotted line, short dashed green and the long dashed blue lines, respectively. Right: Same as left but for $T_{\text{eff}}=1500$ K.

(4.8-10 Gyrs) to investigate a first look comparison with model predictions for a T dwarf or such age and $T_{\text{eff}}$, which was estimated as 1200-1500K using the spectral type-$T_{\text{eff}}$ determinations from Golimowski et al. (2004) as a guide. In order to make a first comparison with model atmosphere predictions we made comparisons between the observed spectrum and synthesised spectra obtained using the atmospheric radiative transfer code, Phoenix (Allard et al. 2001) and the Lyon dust-free COND models. We considered two values of $T_{\text{eff}}$ (1200 and 1500K), three values of $\log g$ (5.0, 5.25 and 5.5) and three metallicities (+0.3, 0.0 and $-0.5$, representing the range observed in the galactic disk; e.g. Holmberg et al. 2007; Jenkins et al. 2008). The resulting comparisons with model spectra are shown spectra in Fig.3. As can be seen non of the fits are particularly good across the whole spectral range and by eye the best fit to the overall fit comes from a 1500K, solar metallicity, high gravity model. This suggests that ULAS J1459+0857 probably has solar to slightly sub-solar metallicity and high gravity. This is instructive at least that the observed properties of ULAS J1459+0857 appear to be in general agreement with those predicted by evolutionary models. While the models clearly have some shortcomings they appear to be broadly consistent with observations for a mid T dwarf of age $>4$ Gyrs.

THE FUTURE: ONLINE SURVEYS.

With the advent of large area, deep optical and NIR surveys, such as UKIDSS, VISTA, VST and WISE many more such white dwarfs + BD binary systems should be identified. For example the coverage of the Vista VIKING and VHS surveys will cover 3 times the area of the UKIDSS LAS at depths of 1.5 mags deeper than UKIDSS and 5 mags deeper than 2MASS. It has been suggested it will provide up to 10 times the number of T dwarfs that are expected to be identified in the UKIDSS LAS. In addition WISE will provide accurate temperatures of such binary components providing complete spectral coverage and good bolometric fluxes, giving reliable temperatures. This will be provide excellent benchmark systems and help place hard constraints on models.
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REFERENCES

Liebert J., 1988, PASP, 100, 1302

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