WD0837+185: THE FORMATION AND EVOLUTION OF AN EXTREME MASS-RATIO WHITE-DWARF–BROWN-DWARF BINARY IN PRAESEPE

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ABSTRACT

There is a striking and unexplained dearth of brown dwarf companions in close orbits (<3 AU) around stars more massive than the Sun, in stark contrast to the frequency of stellar and planetary companions. Although rare and relatively short-lived, these systems leave detectable evolutionary end points in the form of white-dwarf–brown-dwarf binaries and these remnants can offer unique insights into the births and deaths of their parent systems. We present the discovery of a close (orbital separation ~ 0.006 AU) substellar companion to a massive white dwarf member of the Praesepe star cluster. Using the cluster age and the mass of the white dwarf, we constrain the mass of the white dwarf progenitor star to lie in the range $3.5\text{--}3.7 M_{\odot}$ (B9). The high mass of the white dwarf means the substellar companion must have been engulfed by the B star’s envelope while it was on the late asymptotic giant branch (AGB). Hence, the initial separation of the system was ~ 2 AU, with common envelope evolution reducing the separation to its current value. The initial and final orbital separations allow us to constrain the combination of the common envelope efficiency (α) and binding energy parameters (λ) for the AGB star to $\alpha\lambda \sim 3$. We examine the various formation scenarios and conclude that the substellar object was most likely captured by the white dwarf progenitor early in the life of the cluster, rather than forming in situ.

Key words: binaries: close – brown dwarfs – white dwarfs

Online-only material: color figure

1. INTRODUCTION

There is a known dearth of brown dwarf companions to solar-type stars with orbital periods <5 yr (equivalent to orbital separations <3 AU) when compared with lower mass planetary companions or more massive stellar companions (Grether & Lineweaver 2006). There is also some evidence that this paucity of objects may extend to much larger separations (McCarthy & Zuckerman 2004). The reason for the lack of brown dwarf companions at these separations is unknown, but it is likely related to the formation mechanisms involved.

The difficulties in identifying brown dwarfs with early-type companions mean the most extreme examples of these binary systems are found in a highly evolved form: white-dwarf–brown-dwarf binaries. However, detached brown dwarf and very low mass stellar companions to white dwarfs are rare; the fraction of L-type secondaries to white dwarfs is just $0.4\% \pm 0.3\%$ (Steele et al. 2011). Proper-motion surveys and searches for IR excesses have so far found only a handful of confirmed examples (Becklin & Zuckerman 1998; Farihi & Christopher 2004; Maxted et al. 2006; Steele et al. 2007, 2009; Burleigh et al. 2011; Day-Jones et al. 2011; Debes et al. 2011), none of which have a reliably determined age independent of the white dwarf parameters. There are only two systems, WD0137-349B (L8, $0.053 M_{\odot}$; Maxted et al. 2006) and GD1400B (L6–L7, $0.07\text{--}0.08 M_{\odot}$; Farihi & Christopher 2004; Burleigh et al. 2011) ($P_{\text{orb}} = 116$ minutes and 9.8 hr, respectively) where the brown dwarf is known to have survived a phase of common envelope (CE) evolution. This phase of binary star evolution involves the brown dwarf being engulfed by, and immersed in, the expanding atmosphere of the white dwarf progenitor as it evolves away

from the main sequence (see, e.g., Davis et al. 2012). In this Letter, we present the discovery a new white-dwarf–substellar binary system in the Praesepe open star cluster. We show how the cluster age along with the mass and cooling age of the white dwarf can be used to place two independent limits on the mass of the white dwarf progenitor star and, additionally, to constrain the initial orbital radius of the brown dwarf. We use this information to examine the physics of CE evolution and to test formation models for the original system.

2. OBSERVATIONS

We originally obtained high-resolution optical spectra of the $0.798 \pm 0.006 M_{\odot}$ white dwarf WD0837+185 to confirm its membership of the 625 ± 50 Myr old Praesepe open star cluster and discovered that its radial velocity was varying (Casewell et al. 2009), but that it was not a double lined spectroscopic binary. Subsequently, 22 follow-up observations were acquired between 2008 February 7 and 2008 March 11 from the Very Large Telescope’s Ultraviolet Echelle Spectrograph. These data were obtained with exposure times of 20 minutes in thin cirrus, with seeing between 0.5 and $2''.0$. Each pair of consecutive data sets (obtained ~ 1 minute apart) were co-added to increase the signal-to-noise ratio. The data were obtained with the same grating settings, reduced and analyzed as in Casewell et al. (2009). These new measurements verified the variation with a best-fitting period of 4.2 hr, confirming the presence of an unseen companion. The velocity semi-amplitude calculated from the system parameters is $K = v_{\star} \sin i = 11.31 \pm 1.55 \text{ km s}^{-1}$ (Figure 1), giving a minimum mass for the companion $M \sin i \approx 25 M_{\text{Jup}}$.

Figure 1. Radial velocity phase diagram: the radial velocity data folded on the most likely period of 4.2 hr. $v_* \sin i = 11.31 \pm 1.55 \text{ km s}^{-1}$.

We also obtained photometry from the United Kingdom Infrared Telescope (UKIRT) using the UKIRT Fast Track Imager in the *J*, *H*, and *K* bands. These data had exposure times of 3000 s in the *K*, 1200 s in the *H*, and 600 s in the *J* band using a five-point jitter pattern. The data were reduced using the STARLINK package ORAC-DR, and the photometry performed using IRAF. We also observed WD0837+185 with the *Spitzer* space telescope using IRAC in the [3.5] and [4.5] μm bands (Cycle 7; program ID: 57771; PI: Casewell). These data were reduced using the MOPEX pipeline, and the aperture photometry performed using APEX before the pixel phase, array location, and aperture corrections were applied.

3. RESULTS

A comparison of optical photometry from the Sloan Digital Sky Survey (SDSS), near-infrared photometry obtained with UKIRT, the UKIRT Infrared Deep Sky Survey, and mid-infrared images from *Spitzer* with a pure hydrogen atmosphere white dwarf model for WD0837+185 ($T_{\text{eff}} = 15,000 \text{ K}$, $\log g = 8.3$; Casewell et al. 2009), and the hydrogen model combined with observed spectra of a T5, and a T8 dwarf showed that no excess emission, indicative of a companion, is seen. However, if we increase the errors to the 3σ level there is a possibility of an excess in the [3.6] and [4.5] μm wavebands if the white dwarf has a T8 or cooler companion (Figure 2).

WD0837+185 has a luminosity, proper motion, radial velocity, cooling age, and gravitational redshift consistent with being a member of Praesepe (Casewell et al. 2009). If the unseen companion were another white dwarf, this would increase the total luminosity and make it inconsistent with Praesepe membership. Even a high-mass ($\sim 1.38 M_{\odot}$) and therefore small-radius white dwarf with a cooling age $\sim$ the cluster age (giving an effective temperature of 25,000 K) would be detected in the optical photometry (Holberg & Bergeron 2006; Tremblay et al. 2011). Moreover, if the secondary were another white dwarf or even

a neutron star the radial velocity solution would require an extremely low inclination orbit ($\sim 1\text{--}4^\circ$; probability $< 2.4 \times 10^{-3}$) to hide its influence. Hence, we rule out the possibility that WD0837+185B is another white dwarf or a neutron star. WD0837+185 is not coincident with an X-ray source in the *ROSAT* all sky survey, eliminating the possibility that the system contains an accreting black hole. The probability of the system containing a non-accreting black hole is 6×10^{-6} , as the inclination would need to be extremely low ($\sim 0.2^\circ$) to match radial velocity measurements.

The photometry in the [4.5] μm band gives the maximum possible mass of a non-degenerate secondary as $30 M_{\text{Jup}}$ (Baraffe et al. 2003). Combined with the minimum mass from the radial velocity solution ($M \sin i \approx 25 M_{\text{Jup}}$) this strongly suggests that the companion is substellar and is likely to be a methane atmosphere T-type brown dwarf (T8 or later) with an effective temperature of $\approx 900\text{--}1100 \text{ K}$ (Baraffe et al. 2003; Figure 2).

We have also obtained *V*-band photometry obtained every 30 s over a total of 5 hr from the Isaac Newton Telescope on La Palma in 2009 March to investigate the possibility of an eclipse in the system. The data show variation at the 0.74% level (peak to peak) on the orbital timescale (Figure 3). This may be indicative of irradiation by the high ultraviolet flux of the white dwarf, possibly leading to substantial temperature differences between the “day” and “night” hemispheres of the T dwarf atmosphere as is seen in WD0137-349 (Maxted et al. 2006). No eclipse is seen, but the probability of an eclipse in this system is only $\sim 9\%$ and any eclipse would only last ~ 3.5 minutes (Faedi et al. 2011), which is difficult to detect with our sampling frequency (30 s exposure + 30 s readout).

The main-sequence lifetime of the white dwarf progenitor is constrained by the difference between the cooling age of WD0837+185 ($313 \pm 5 \text{ Myr}$, determined from the white dwarf temperature, gravity, and appropriate cooling model; Fontaine et al. 2001) and the age of the Praesepe cluster ($625 \pm 50 \text{ Myr}$), which limits the progenitor mass to $3.48 \pm 0.23 M_{\odot}$ equivalent

Figure 2. Photometry and models of WD0837+185: SDSS *ugriz* (triangles), UKIRT *ZYJHK* (boxes) and *Spitzer* [3.6], [4.5] (diamonds) magnitudes shown with a DA white dwarf model spectrum ($T_{\text{eff}} = 15,000$ K, $\log g = 8.3$). 3σ error bars are shown on the *Spitzer* data points. A DA+T5 composite spectrum is also shown as a dashed red line, and a DA+T8 spectrum as the dotted blue line. The T dwarf spectra are real data and are the objects 2MASSJ05591914–1404488 (Cushing et al. 2006) and 2MASSJ04151954–0935066 (Saumon et al. 2007), but the spectra are not continuous as they are *M* and *L* band spectra. There are gaps between 4.1 and 5.2 μm .

(A color version of this figure is available in the online journal.)

Figure 3. Light curve from 2009 March binned by a factor of seven folded on the orbital period of 4.2 hr. The peak to peak variation is at 0.74%.

to a spectral type B9. Intriguingly, the orbit of WD0837+185B (orbital separation ~ 0.006 AU $\sim 1.24 R_{\odot}$) is well within the main sequence radius of a B9 star ($R \sim 3 R_{\odot}$; Marigo et al. 2008). WD0837+185B is unlikely to have been captured into this current orbit as the star-crossing timescale in Praesepe is a few Myr and the low stellar density (20 starspc^{-2} ; Kraus & Hillenbrand 2007) makes the typical close encounter ($\ll 1$ AU) timescale much longer than the age of the universe. The system therefore must have gone through a phase of CE evolution. This brief evolutionary phase is a key stage in the formation of short-period binary systems and occurs when the lower mass companion becomes engulfed by the nuclear-evolution-driven expansion of the primary star’s envelope. The binary orbit then decays rapidly as drag forces unbind the primary’s envelope at the expense of orbital energy.

The mass of WD0837+185 ($\sim 0.8 M_{\odot}$) is at the very upper end of core masses attainable within the errors on the progenitor star mass. Models relating initial stellar mass to core mass (taken to be the white dwarf mass) at first thermal pulse (Karakas et al. 2002) give a lower limit of $\sim 3.6 M_{\odot}$ for the progenitor mass, while the cooling-age–cluster-age argument above provides an upper limit of $\sim 3.7 M_{\odot}$. The very limited overlap between these independent mass estimates show that the progenitor star engulfed the brown dwarf very late in its evolution on the asymptotic giant branch (AGB). The radius of the progenitor at this point, and hence the orbital separation of WD0837+185B at the onset of the CE phase, would have been ~ 2 AU (Ventura & Marigo 2009). This estimate places the orbital separation of the original system well within the region where there is an observed dearth of brown dwarf companions to solar-type stars.

Treatments of CE evolution are usually parameterized in terms of the efficiency with which orbital energy is transferred to the envelope of the primary star (α) and a parameter governing the binding energy of the primary’s envelope (λ) (see, e.g., Davis et al. 2012; Xu & Li 2010), the latter being defined by

$$E_{\text{bind}} = -\frac{GM_1 M_{\text{env}}}{\lambda R_1}, \quad (1)$$

where E_{bind} is the binding energy, M_1 is the progenitor (primary) mass, M_{env} is progenitor envelope mass, and R_1 is the progenitor’s radius. Many population synthesis calculations treat λ as a constant, but its value is poorly constrained. Treatments differ in the inclusion (or not) of the internal energy of the stellar matter. We are able to place explicit limits on λ because we know that the CE phase began when the WD0837+185 progenitor was on the late AGB, which fixes the original orbital radius as well as the core and the envelope mass of the progenitor. Knowledge

of the initial ($a_i \sim R_1$) and final (a_f) orbital separations allows the combination $\alpha\lambda$ to be extracted from the energy balance equation

$$\alpha\lambda \left(\frac{GM_{\text{core}}M_2}{2a_f} - \frac{GM_1M_2}{2a_i} \right) = \frac{GM_1M_{\text{env}}}{R_1}, \quad (2)$$

where M_2 is the brown dwarf mass and $M_{\text{core}} (= M_1 - M_{\text{env}})$ is the progenitor core mass. For a progenitor mass $3.6 M_{\odot}$ and a companion mass of $30 M_{\text{Jup}}$, the combination $\alpha\lambda \sim 3$ is required to place the brown dwarf in its current orbit from an initial orbit ~ 2 AU, assuming no significant mass loss by the progenitor at the point of contact (any mass loss would cause a proportionally lower estimate of $\alpha\lambda$). In the case of maximum efficiency ($\alpha = 1$), $\lambda \sim 3$ is very low for a highly evolved $3.6 M_{\odot}$ star if the internal energy of the stellar material is taken into account when calculating λ , but is in reasonable agreement with calculations including only gravitational binding energy (Xu & Li 2010). Highly evolved, late AGB primaries of this mass are precisely those predicted to have the highest values of λ when including the contribution of the internal energy of the stellar matter, and a low λ for these objects is a strong hint that this parameter is of order unity for all primaries.

4. INTERPRETATION

WD0837+185B may have formed (at its original orbital separation) in one of two ways: in a manner similar to solar system and extrasolar giant planets, or as an extreme mass-ratio binary star. The planetary channel assumes formation in a disk around the newly formed star, and consists of two options: core accretion or gravitational instability. Core accretion is not a promising formation mechanism here: tidal torques from the planet strongly suppress gas accretion from the disk on to the planet for masses $\gtrsim 5 M_{\text{Jup}}$ (D’Angelo et al. 2002), and it is unlikely that objects as massive as $\sim 20 M_{\text{Jup}}$ can ever form in this manner. Moreover, the growth timescale for such a massive object is at least comparable to the typical lifetime of protoplanetary disks around B stars (which are estimated to be Myr or less; Hillenbrand et al. 1992).

Disk fragmentation via gravitational instability can result in the formation of much more massive objects, and is a plausible scenario for brown dwarf formation (e.g., Stamatellos et al. 2007), but carries the caveat that protostellar disks are gravitationally unstable only at large radii. For a $3.5 M_{\odot}$ star a self-luminous disk is only unstable at radii ≥ 70 AU (Matzner & Levin 2005; Rafikov 2009), and this critical radius increases when irradiation from the star is taken into account. The question then becomes whether a brown dwarf can migrate inward to 1–2 AU from its formation radius at ~ 100 AU. Dynamical “hardening” of the system via repeated encounters with other cluster stars is extremely unlikely, as repeated such interactions are more likely to disrupt the system than shrink its orbit; also, the low stellar density in Praesepe essentially rules out this mechanism. Inward migration via gravitational interactions with other brown-dwarf- or planetary-mass objects (so-called planet–planet scattering) is possible, but again unlikely: the process is chaotic, but simulations find that inward migration via this mechanism is usually modest (e.g., Raymond et al. 2008); the probability of being scattered from ~ 100 AU to ~ 1 –2 AU is very small. The final possibility is gas-driven migration before the dispersal of the protostellar disk. Giant planets typically migrate in the Type II regime. Although the discovery of two hot Jupiters around stellar members of Praesepe by Quinn et al.

(2012) shows that planet formation and migration in the Type II regime has occurred in this open cluster, it is unlikely that objects as massive as $\sim 25 M_{\text{Jup}}$ can ever form in this manner. For an object of 25 – $30 M_{\text{Jup}}$ Type II migration is strongly suppressed and proceeds on a timescale much longer than the lifetime of the gas disk (Syer & Clarke 1995), but recent simulations have found that migration in gravitationally unstable disks can in fact be very rapid (Cha & Nayakshin 2011; Baruteau et al. 2011). It is unclear, however, whether it is possible to halt the rapid migration of 20 – $30 M_{\text{Jup}}$ objects at ~ 1 AU, and prevent them falling all the way on to the central star. This mechanism cannot be ruled out without further investigation, but we do not consider it to be the most likely formation channel for WD0837+185B.

Binary stars form from the fragmentation of star-forming molecular cores, but are affected by the cluster dynamics as they evolve. Extreme mass-ratio binaries in close orbits such as this one ($q \simeq 0.01$) are very rare. Forming such systems in a similar manner to binary stars is challenging because circumstellar material preferentially accretes on to the secondary, increasing its mass and driving the binary mass ratio toward $q = 1$ (Artymowicz 1983). Many theoretical studies have investigated how dynamical interactions may harden initially wide binaries, or destroy them, but the fundamental physics of binary formation remains poorly understood (see, e.g., Goodwin et al. 2007 and references therein).

The one remaining formation theory left for consideration is thus dynamical capture. Recent numerical simulations (Bate 2011) show that in an $N \sim 100$ – 500 cluster a few objects are formed this way, though due to the low number statistics it is not clear how frequently extreme mass-ratio objects are captured into $\sim$ AU orbits. Praesepe has more members than in this example ($N \sim 1000$; Kraus & Hillenbrand 2007), and at its current age, is likely to have undergone dynamical evolution, decreasing the cluster population by as many as half, and preferentially ejecting the lowest mass cluster members (de La Fuente Marcos & de La Fuente Marcos 2002). The most plausible formation scenario for WD0837+185B is therefore likely to be dynamical capture where the brown dwarf has been inserted into the binary after its formation. This is likely to be a common formation scenario for those relatively rare oases in the brown dwarf desert: high mass-ratio main sequence plus brown dwarf pairs found by radial velocity surveys with separations of a few AU (e.g., Omiya et al. 2011).

5. CONCLUSIONS

We confirm that WD0837+185 is a radial velocity variable object and conclude from optical, near-IR, and mid-IR photometry that the probable companion is a 25 – $30 M_{\text{Jup}}$ late T dwarf. Optical photometry also tentatively indicates that the white dwarf is irradiating its substellar companion, although no eclipse is seen in the data.

Using the cluster age and the mass of the white dwarf, we constrain the mass of the white dwarf progenitor star to lie in the range 3.5 – $3.7 M_{\odot}$ (B9). The high mass of the white dwarf means the substellar companion must have been engulfed by the B star’s envelope while it was on the late AGB. Hence, the initial separation of the system was ~ 2 AU, with CE evolution reducing the separation to its current value. The initial and final orbital separations allow us to constrain the combination of the CE efficiency (α) and binding energy parameters (λ) for the AGB star to $\alpha\lambda \sim 3$. We examine the various formation scenarios and conclude that the substellar object was most likely

captured by the white dwarf progenitor early in the life of the cluster, rather than forming in situ.

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