Discovery of a stripped red giant core in a bright eclipsing binary star

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Abstract. We report the serendipitous discovery from WASP archive photometry of a binary star in which an apparently normal A-type star (J0247−25 A) eclipses a smaller, hotter subdwarf star (J0247−25 B). The kinematics of J0247−25 A show that it is a blue-straggler member of the Galactic thick-disk. We present follow-up photometry and spectroscopy from which we derive approximate values for the mass, radius and luminosity for J0247−25 B assuming that J0247−25 A has the mass appropriate for a normal thick-disk star. We find that the properties of J0247−25 B are well matched by models for a red giant stripped of its outer layers and currently in a shell hydrogen-burning stage. In this scenario, J0247−25 B will go on to become a low mass white dwarf (M ≃ 0.25M☉) composed mostly of helium. J0247−25 B can be studied in much greater detail than the handful of pre helium white dwarfs (pre-He-WD) identified to-date. These results have been published by Maxted et al. (2011). We also present a preliminary analysis of more recent observations of J0247−25 with the UVES spectrograph, from which we derive much improved masses for both stars in the binary. We find that both stars are more massive than expected and that J0247−25 A rotates sub-synchronously by a factor of about 2. We also present lightcurves for 5 new eclipsing pre-He-WD subsequently identified from the WASP archive photometry, 4 of which
Maxted et al. have mass estimates for the subdwarf companion based on a pair of radial velocity measurements.

1. Discovery of J0247−25

The WASP survey (Wide Angle Search for Planets, [Pollacco et al. 2006]) uses two instruments to monitor the brightness of millions of stars in both hemispheres. Each instrument has 8 e2V CCD cameras with 200 mm f/1.8 Canon lenses to produce images covering approximately 8° × 8° on the sky per camera. Two 30s exposures are obtained on selected fields every 5–10 minutes every clear night. The strategy is optimised for the detection of planetary transits for stars with V≈ 9–13. The techniques used to identify planetary transits in the WASP data are also very effective at identifying eclipsing binary stars. One star flagged as an eclipsing binary star as part of this process was 1SWASP J024743.37−251549.2 (J0247−25 hereafter). The WASP lightcurve of this star is shown as a function of orbital phase with the period 0.6678 d in Fig.1. The shape and depths of the eclipses in this lightcurve show that the feature at phase 0 is the total eclipse of a smaller but hotter star by its larger and cooler companion. The catalogue photometry available show that the larger star (J0247−25 A), which contributes ∼90% of the optical light, is an A-type star, so we obtained follow-up observations to determine the nature of the smaller, hotter star. Photometry with the SAAO 1.0-m telescope (Fig.1) confirmed our interpretation of the WASP lightcurve. Spectroscopy with a variety of instruments was used to confirm the mid-A spectral type of J0247−25 A and to measure its the spectroscopic orbit (Fig. 2). We used the lightcurve model EBOP (Etzel 1981; Popper & Etzel 1981) to analyse the WASP and SAAO 1.0-m lightcurves. The surface brightness ratio we derive from the lightcurve models can be combined with the observed V and K$_S$ magnitudes of J0247−25 to estimate the effective temperatures T$_{\text{eff}, A}$ ≈ 8060K and T$_{\text{eff}, B}$ ≈ 13400K. The surface gravity of J0247−25 B, log g$_B$ = 4.76 ± 0.05, can be derived directly from the parameters of the lightcurve model and the mass function. In Fig.3 we compare these values of T$_{\text{eff}, B}$ and log g$_B$ to the effective temperatures and surface gravities of 298 faint blue stars observed by Saar et al. (1997). It is clear that J0247−25 B is unusually cool given its surface gravity and sits well below the main sequence (long-dashed lines) and the zero-age horizontal branch (short-dashed lines).

The kinematics of J0247−25 show that it is a member of the Galactic thick disk, which suggests that it is likely to be old (≥ 7 Gyr), metal poor (−1 ≤ [Fe/H] ≤ −0.3) and have enhanced α-element abundance ([Mg/Fe] ≥ 0.3). The density of J0247−25 A, $\rho_A = 0.29 \pm 0.02 \rho_\odot$, can be derived directly from the parameters of the lightcurve model and the mass function. We compare the values of T$_{\text{eff}, A}$ and $\rho_A$ to stellar models for the appropriate composition in Fig. 4. This comparison leads to an estimate of $M_A = 1.5 \pm 0.1 M_\odot$ for the mass of J0247−25 A and, via the mass function, a mass estimate of $M_B = 0.23 \pm 0.03 M_\odot$ for J0247−25 B.

In Fig. 5 we compare the position of J0247−25 B in the Hertzsprung-Russell diagram to evolutionary tracks for the formation of low mass white dwarfs (M ≈ 0.2$M_\odot$) as a result of drastic mass loss from low mass red giant stars. The observed properties of J0247−25 B are well matched by such models during the phase when the star is evolving bluewards at almost constant luminosity due to p-p shell-hydrogen burning in the thin hydrogen envelope. In this scenario J0247−25 B will become a low mass
Figure 1. Lightcurves of J0247−25. From bottom-to-top: WASP white-light photometry with lightcurve model fit, SAAO 1.0-m Ic-band and V-band.

Figure 2. Left panel: GMOS-S spectrum of J0247−25. Right panel: Radial velocities of J0247−25 A with a circular orbit fit. The spectrograph used is indicated as follows: filled circles – EFOSC2; triangles – ISIS; diamonds – GMOS.

A white dwarf composed almost entirely of helium, so we dub it a pre helium white dwarf (pre-He-WD). Also shown in Fig. 5 are other He-WD and pre-He-WD. The parameters of the related objects are listed in Table 1.

A complete description of the discovery and characterisation of J0247−25 has been accepted for publication in MNRAS (Maxted et al. 2011).
2. UVES spectroscopy of J0247–25

We obtained high resolution, high signal-to-noise spectroscopy of J0247–25 with the UVES echelle spectrograph on the VLT 8.2-m UT2 telescope. Service mode observations were used to obtain 46 spectra covering the quadrature phases of the orbit and 12 spectra during the total eclipse, i.e., spectra of J0247–25 A alone. A small section of these spectra around the Mg II 4481 Å line is shown in Fig. 6. The narrow Mg II line from J0247–25 B can be seen moving in anti-phase to the broader and stronger spectral lines of J0247–25 A. The mean spectrum obtained during total eclipse was used as a template to measure the radial velocity of J0247–25 A by cross correlation. We then subtracted the mean spectrum of J0247–25 A from the 46 out-of-eclipse spectra after shifting it by the appropriate radial velocity and scaling it by an estimate of the luminosity ratio at this wavelength. This process revealed the underlying spectrum of J0247–25 B. We measured the radial velocity of J0247–25 B using a gaussian fit to the Mg II 4481 Å line in these spectra. We then shifted and added these spectra to produce the mean spectrum of J0247–25 B shown in Fig. 7. Also visible in this spectrum are a weak He I 4471 Å line and the broad Hγ line.

The radial velocities measured from these UVES spectra combined with the inclination from the lightcurve model imply masses of $M_A = 2.07 \pm 0.015 M_\odot$ and $M_B = 0.29 \pm 0.005 M_\odot$. The coverage of the UVES spectra is greater than the limited results presented here and several other spectral lines from J0247–25 B are visible, so it will be possible to further improve these mass estimates. Even so, it is clear that the masses...
Figure 4. Location of the J0247−25 A in the $T_{\text{eff}}$ – density ($\rho$) plane compared to evolutionary models for normal stars with masses as noted and [Fe/H] = −0.65 from Girardi et al. (2000).

of both J0247−25 A and J0247−25 B are larger than expected based on the stellar models we have used above. For J0247−25 A the discrepancy between the mass observed and that expected based on stellar models is similar to that observed by Kaluzny et al. (2007) for V209 ω Cen A, the companion to the pre-He-WD V209 ω Cen B in an eclipsing binary member of the globular cluster ω Cen.

We have measured a projected rotational velocity of $V_{\text{rot}} \sin i = 95 \pm 5$ km s$^{-1}$ for J0247−25 A from the rotational broadening of its spectral lines. With our improved mass estimates from the UVES spectroscopy we find that this is approximately half the rotational velocity expected if J0247−25 A rotates synchronously with the orbit.

3. New eclipsing pre-He-WD

We have inspected several thousand lightcurves of stars flagged as eclipsing binary stars in the WASP archive to look for new examples of eclipsing pre-He-WD similar to J0247−25. The features we looked for in the lightcurve were: a total eclipse with a depth of about 10%; sharp ingress/egress to the total eclipse; a visible secondary eclipse. The lightcurves of 6 stars satisfying these criteria, including J0247−25, are shown in Fig. 5. The properties of these stars are given in Table 2. The spectral type of the stars has been estimated from the catalogue photometry available for these stars. Only J1323+43 (EL CVn) has been previously identified as an eclipsing binary star (Koen & Eyer 2002).
Figure 5. Location of the J0247−25 B and related objects in the Hertzsprung–Russell diagram. Models for the formation of low mass white dwarfs (with final masses as noted, bottom-to-top) are also shown as follows: Driebe et al. (1999) – solid lines (0.195M_⊙ and 0.234M_⊙); Nelson et al. (2004) – dotted lines (0.205M_⊙ and 0.215M_⊙); van Kerkwijk et al. (2010) – dashed lines (0.21M_⊙).

Table 1. Masses and periods for low mass white dwarfs and pre-He-WDs in binary systems.

<table>
<thead>
<tr>
<th>Name</th>
<th>Period [d]</th>
<th>Mass[ M_⊙]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 6121-V46</td>
<td>0.087</td>
<td>~0.19</td>
<td>O’Toole et al. (2006)</td>
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<tr>
<td>HD 188112</td>
<td>0.607</td>
<td>0.24±0.07</td>
<td>Heber et al. (2003)</td>
</tr>
<tr>
<td>J0247−25 B</td>
<td>0.668</td>
<td>0.26±0.03</td>
<td>This paper</td>
</tr>
<tr>
<td>PC1-V36</td>
<td>0.794</td>
<td>0.056 ± 0.018</td>
<td>Kaluzny et al. (2007)</td>
</tr>
<tr>
<td>V209 ω Cen B</td>
<td>0.834</td>
<td>0.144 ± 0.008</td>
<td>Kaluzny et al. (2007)</td>
</tr>
<tr>
<td>KIC 10657664</td>
<td>3.274</td>
<td>0.26 ± 0.04</td>
<td>Carter et al. (2011)</td>
</tr>
<tr>
<td>KOI-75</td>
<td>5.189</td>
<td>0.37 ± 0.08</td>
<td>van Kerkwijk et al. (2010)</td>
</tr>
<tr>
<td>KOI-81</td>
<td>23.89</td>
<td>0.22 ± 0.03</td>
<td>van Kerkwijk et al. (2010)</td>
</tr>
<tr>
<td>Regulus B</td>
<td>40.11</td>
<td>&gt;0.30</td>
<td>Gies et al. (2008)</td>
</tr>
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</table>

For 4 of these stars we have obtained two spectra with the TWIN spectrograph on the CAHA 3.5-m telescope, one at each of the quadrature phases. Observations were obtained with a low resolution grating on the blue arm covering the wavelength range 3290–5450Å. These spectra have been used to confirm that the spectral types given
in Table 2 are approximately correct but have not yet been analysed any further. The red arm observations have a resolution of approximately 1.5 Å and cover the Hα lines. We used least squares fitting to determine an empirical line profile for the Hα line in each star composed of the sum of 3 gaussian functions. This empirical line profile was then used to measure the radial velocity of the star at the two quadrature phases observed. We then assumed a mass for the brighter component of each binary based on its spectral type and used the mass function to estimate the masses for the fainter pre-He-WD components given in Table 2.

4. Discussion

J0247−25 B is an ideal system for testing in detail models for the formation of low mass helium white dwarfs. It is a bright star, much brighter than the more distant examples of pre-He-WD found in globular clusters. It is a double-lined eclipsing binary star and so it is possible to measure precise, model-independent masses and radii for both stars in the binary. This is not possible for most of the other pre-He-WD listed in Table 1. The total eclipses and moderate luminosity ratio of this binary make it possible to recover a high quality spectrum of the pre-He-WD in this binary, as we have shown for our UVES spectra. This will make it possible to measure properties of J0247−25 B such as its rotational velocity, effective temperature and surface composition. This may make it possible to test the prediction of some evolutionary models that objects such as J0247−25 B should be hydrogen deficient. Some low mass white dwarfs are expected to undergo a number of unstable flashes of CNO hydrogen burning during their early
evolution. The occurrence of these flashes depends critically on the mass of hydrogen that remains on the surface of the star, which in turn depends on the mass loss history of the star. Understanding these hydrogen shell flashes is crucial for a better understanding of all low mass white dwarfs, particularly the low mass white dwarf companions to millisecond pulsars. It may be possible to put useful constraints on the hydrogen envelope mass in J0247−25 B by comparing its total mass to the core mass inferred from its luminosity. The sub-synchronous rotation of J0247−25 A is rather surprising given that it is expected to have gained rather a lot of mass and angular momentum from the red giant progenitor of J0247−25 B. It may be that this star is currently far from equilibrium. A detailed reconstruction of the evolutionary history of J0247−25 will lead to a much better understanding of how stars react to mass accretion. This will obviously be interesting for improving our understanding of binary star evolution, but may have wider implications, e.g., episodic accretion may be the process that dominates the observed properties of pre main-sequence stars (Baraffe et al. 2009). The kinematics of J0247−25 also imply useful constraints on the composition and age of this binary star.

The discovery of several other eclipsing pre-He-WD opens up the possibility of exploring how the formation of these objects varies with parameters such as the initial masses and orbital periods of the binary. It also makes the tests of the evolution models for these objects much stronger because fine tuning of parameters or extraordinary evolutionary scenarios that might be invoked to explain the formation of a single object cannot be justified when several similar examples exist. It may also be possible to put
useful constraints on the space density of such objects since the WASP survey seems to be very effective at detecting these short period eclipsing binaries.

![WASP lightcurves of eclipsing pre-HE-WD.](image)

**Figure 8.** WASP lightcurves of eclipsing pre-HE-WD.

<table>
<thead>
<tr>
<th>Star</th>
<th>Spectral Type</th>
<th>V [mag]</th>
<th>Period [d]</th>
<th>M₂ [M☉]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0247−25</td>
<td>A6</td>
<td>11.9</td>
<td>0.668</td>
<td>0.29</td>
</tr>
<tr>
<td>J1323+43</td>
<td>A1</td>
<td>9.4</td>
<td>0.795</td>
<td>~ 0.2</td>
</tr>
<tr>
<td>J1625−04</td>
<td>A7</td>
<td>10.4</td>
<td>1.526</td>
<td>~ 0.15</td>
</tr>
<tr>
<td>J1628+10</td>
<td>F6</td>
<td>12.9</td>
<td>0.720</td>
<td>~ 0.05</td>
</tr>
<tr>
<td>J2101−06</td>
<td>A2</td>
<td>11.5</td>
<td>1.290</td>
<td>~ 0.2</td>
</tr>
<tr>
<td>J2328−39</td>
<td>A6</td>
<td>13.3</td>
<td>0.769</td>
<td>~</td>
</tr>
</tbody>
</table>

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References