The double degenerate system NLTT 11748*

A. Kawka¹, S. Vennes¹,², and T.R. Vaccaro²,³

¹ Astronomický ústav, Akademie věd České republiky, Frčova 298, CZ-251 65 Ondřejov, Czech Republic e-mail: kawka,vennes@sunstel.asu.cas.cz
² Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
³ Department of Physics & Astronomy, Francis Marion University, Box 100547, Florence, SC 29501, USA e-mail: tvaccaro@fmarion.edu

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ABSTRACT

We show that the extremely low-mass white dwarf NLTT 11748 (0.17 M⊙) is in a close binary with a fainter companion. We obtained a series of radial velocity measurements of the low-mass white dwarf using the Ha core and determined an orbital period of 5.64 hours. The velocity semi-amplitude (K = 274.8 km s⁻¹) and orbital period imply that it is a degenerate star, and that the minimum mass for the companion is 0.75 M⊙ (assuming a mass of 0.167 M⊙ for the primary). Our analysis of Balmer line profiles shows that a 0.75 M⊙ white dwarf companion does not contribute more than 2% or 5% of the flux (V-band) for helium- or hydrogen-rich surfaces, respectively. The kinematics of the system suggest that it belongs to the Galactic halo.

Key words. stars: binaries: close – stars: individual: NLTT 11748 – white dwarfs

1. Introduction

The high proper-motion star NLTT 11748 was identified as an extremely low-mass (ELM) white dwarf by Kawka & Vennes (2009). The first ELM white dwarfs were discovered to be companions to neutron stars (e.g., van Kerkwijk et al., 1996; Bassa et al., 2003), but recent follow-up observations of ELM white dwarfs identified in colourimetric or proper motion surveys (e.g., SDSS, NLTT) often find them to be in a close binary with a white dwarf companion (e.g., SDSS J125733.63+542850.5, Badenes et al., 2009; Kulkarni & van Kerkwijk, 2010; Marsh et al., 2010). The companions of several other ELM white dwarfs found to be in close binary systems are yet to be formally identified, but they are likely to be more massive white dwarfs (see, e.g., Agüeros et al., 2009a,b).

The stellar and kinematical properties of NLTT 11748 (Kawka & Vennes, 2009) and of two similar objects, LP400-22 (Kilic et al., 2009; Vennes et al., 2009) and SDSS J1053+542850.5 (Badenes et al., 2009; Kulkarni & van Kerkwijk, 2010; Marsh et al., 2010), also suggest that they are old halo stars. The constraints placed on their total ages help retrace the prior evolution of these systems (see Tauris & Savonije, 1993; Nelemans et al., 2001; Nelson et al., 2004).

The formation of ELM white dwarfs requires that the systems go through at least two phases of mass transfer, where the second mass transfer phase strips the less massive companion of its outer envelope before the helium ignition. This generic scenario appears valid whether the more massive component is a neutron star or a white dwarf (see for example Nelemans et al., 2001; Nelson et al., 2004). An example of a possible progenitor to an ELM white dwarf is the bright subluminous B (sdB) star, HD 188112 (Heber et al., 2003). The subdwarf star has a lower mass than average, 0.24 versus ~ 0.5 M⊙ (Zhang et al., 2009), and orbits a degenerate companion with a mass ≥ 0.73 M⊙ every 14.6 hours. The subdwarf is a likely progenitor of a helium white dwarf similar to NLTT 11748. On the other hand, a possible progenitor to an ELM white dwarf with, this time, a neutron star companion is SDSSJ102347.6+003841 (Wang et al., 2009). This is a close binary comprising a G-type star and a 1.69ms pulsar (Archibald et al., 2009) with an orbital period of 4.75 hours. Although the spectral type of the visible component implies a mass of ≈ 1 M⊙, the mass ratio of the system dictates a much lower mass of ~ 0.2 M⊙ suggesting that the star is significantly evolved with a helium-enriched core. This system probably represents a first link between low-mass X-ray binaries and ELM plus neutron star binaries (Archibald et al., 2009).

We report new observations that help clarify the nature of the ELM white dwarf NLTT 11748. We obtained two sets of intermediate resolution spectra that show that NLTT 11748 is in a close binary system (Sect. 2). Our analysis of the spectroscopic data and a first determination of the binary parameters are presented in Sect. 3. We discuss our results in Sect. 4 and summarise in Sect. 5.

2. Observations

We observed NLTT 11748 with the FORS2 spectrograph attached to the UT1 - Antu at Paranal on UT 2009 October 22 and 23. We used the 1200R grism combined with a slit width of 1", which provided a resolution of 3.0 Å. The spectra were obtained as part of a programme aimed at detecting and measuring magnetic fields in hydrogen-rich white dwarf stars. The observation sequence consists of two consecutive exposures with the Wollaston prism rotated by 90 degrees between them. In principle, a magnetic field may cause an apparent velocity offset in pairs of exposures, but our analysis of the radial velocity measurements excludes the effect of a magnetic field (Sect. 3.1).
3. Analysis

3.1. Binary parameters

We used the Hα line centre to measure the radial velocity of NLTT 11748. We fitted a Gaussian profile to the deep, narrow core. Repeated measurements varying the fitting window from 2 to 5 Å from the line centre were averaged, leaving residuals of 3 to 10 km s\(^{-1}\) depending on the signal-to-noise ratio of the spectrum. The velocities were then corrected to the solar system barycentre. We verified the procedure by cross-correlating each spectrum with a template built by co-adding all spectra in the rest frame (see Fig. 1) and comparing the resulting velocities to the Gaussian fits. With a window from 6500 to 6620 Å, we found that the two methods differ by \(\Delta v = 1.4 \pm 3.5 \text{ km s}^{-1}\) for the higher quality FORS2 spectra, and \(\Delta v = 3.2 \pm 12.0 \text{ km s}^{-1}\) for the R-C spectra. Accordingly, the FORS2 and R-C spectra are weighted 4:1 in the orbital analysis. Table 1 lists the barycentric mid-exposure times and velocities.

We determined the orbital parameters by fitting sinusoidal functions to the radial velocities, where the period (\(P\)), mean systemic velocity (\(\gamma\)), the velocity semi-amplitude (\(K\)) and the initial epoch (\(T_0\)) are varied. Figure 2 shows the periodogram and best-fit radial velocity curve. The significance values are drawn at 66%, 90% and 99%. The average of the residuals is \(\sim 3 \text{ km s}^{-1}\), commensurate with our estimates of the wavelength scale accuracy. Although the FORS2 spectra were obtained with the Wollaston prism in place, the low residual value excludes a significant magnetic field. A more detailed spectropolarimetric analysis will be reported elsewhere.

The best-fit parameters are
\[
P = 0.235061 \pm 0.000003 \text{ d}, \]
\[
T_0(\text{BJD UT}) = 2455126.712 \pm 0.003, \]

Table 1. Observation log

| Start UT date and time | \(t_{\text{exp}}(s)\) | Start UT date and time | \(t_{\text{exp}}(s)\) |
|------------------------|---------------------|------------------------|---------------------|
| ESO                    |                     | ESO                    |                     |
| 2009 Oct 22 04:31:00   | 1200               | 2009 Oct 22 06:42:14   | 1200               |
| 2009 Oct 22 05:12:09   | 1200               | 2009 Oct 23 04:50:11   | 1200               |
| 2009 Oct 22 05:35:52   | 1200               | 2009 Oct 23 05:11:20   | 1200               |
| 2009 Oct 22 05:57:40   | 1200               | 2009 Oct 23 05:40:44   | 1200               |
| 2009 Oct 22 06:21:15   | 1200               | 2009 Oct 23 06:01:52   | 1200               |

| KPNO                   |                     | KPNO                   |                     |
| 2010 Mar 04 03:19:37   | 1800               | 2010 Mar 05 03:53:24   | 1800               |
| 2010 Mar 04 03:50:25   | 1800               | 2010 Mar 05 04:58:15   | 1800               |
| 2010 Mar 04 04:25:32   | 1800               | 2010 Mar 06 02:42:39   | 1800               |
| 2010 Mar 05 02:53:19   | 1800               |                         |                     |

We obtained additional observations with the R-C spectrograph attached to the 4m telescope at the Kitt Peak National Observatory (KPNO) on UT 2010 March 4 to 6. We used the T2KB detector and the KPC-24 grating (860 lines mm\(^{-1}\)) in second order centred on Hα. We employed the GG495 filter to block out contamination from the first order. We set the slit width to 1.5", which provided a resolution of 0.8 Å (full-width half-maximum).

All spectra were wavelength-calibrated using comparison arc (HeNeAr) exposures. The stability of the wavelength scale was verified through O\(_2\) sky lines, which remained stable with a standard deviation of 3 km s\(^{-1}\). All data were reduced with standard procedures within IRAF. Figure 1 and Table 1 show our spectra and the observation log.

Table 2. Radial velocity measurements of NLTT 11748.

| BJD          | \(v_{\text{bary}}\) (km s\(^{-1}\)) | BJD          | \(v_{\text{bary}}\) (km s\(^{-1}\)) |
|--------------|---------------------------------|--------------|---------------------------------|
| (2455000+)   |                                 | (2455000+)   |                                 |
| 126.71404    | 151.4                           | 126.719129   | 369.5                           |
| 126.72873    | 259.2                           | 127.71352    | 412.2                           |
| 126.74520    | 354.1                           | 127.73282    | 380.7                           |
| 126.75988    | 403.4                           | 127.74863    | 286.5                           |
| 126.77660    | 410.7                           | 127.76330    | 189.2                           |
| 259.64754    | 87.1                            | 260.67090    | −38.4                           |
| 259.66893    | −64.6                           | 260.71593    | 269.0                           |
| 259.69331    | −131.7                          | 261.62168    | 23.5                            |
| 260.62918    | −131.1                          |               |                                 |

![Fig. 1. Spectra obtained with VLT FORS2 (left) and the KPNO R-C spectrograph (right). The spectra are labeled with the orbital phase (Sect. 3.1) and the top spectra are the co-added phase-corrected spectrum for each spectrograph.](image-url)

where \(T_0\) is the initial epoch of superior conjunction of the unseen companion. We also determined the systemic velocity \(\gamma_{\text{sym}} = 136.5 \pm 0.9 \text{ km s}^{-1}\) by subtracting the gravitational redshift of the white dwarf (\(v_g = 2.0 \pm 0.4 \text{ km s}^{-1}\)) from the apparent systemic velocity of \(\gamma = 138.5 \pm 0.8 \text{ km s}^{-1}\). The gravitational redshift of the white dwarf was calculated assuming the parameters derived in Kawka & Vennes (2009). The observed velocity semi-amplitude is \(K = 274.8 \pm 1.5 \text{ km s}^{-1}\), which corresponds to a mass function for the unseen companion of \(f = 0.5054 \pm 0.0083 M_\odot\).

Adopting a mass of 0.167 \(M_\odot\) for the white dwarf (Kawka & Vennes 2009) and using our orbital parameters, we infer a minimum mass for the unseen companion of 0.75 \(M_\odot\). A main-sequence companion with a mass of 0.75 \(M_\odot\) would have an absolute magnitude of \(M_V = 7\) (Henry & McCarthy 1993), which would clearly outshine a white dwarf with \(M_V = 9.7\).
Residuals of the sinusoidal fit.

halo are LP400-22 (Vennes et al., 2009) and SDSSJ1053.

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the Balmer line profiles, their analysis did not consider a com-

We re-evaluated the kinematics of the system with the new

systemic velocity to obtain \((U,V,W) = (-163,-252,29) \text{ km s}^{-1}\).

These updated values clearly place NLTT 11748 in the halo. Two other ELM systems whose kinematics place them in the halo are LP400-22 (Vennes et al., 2009) and SDSSJ1053+5200 (Kilic et al., 2010) with the remaining systems (without a neutron star) apparently belonging to the disc (Kilic et al., 2010).

3.2. Constraints on a white dwarf companion

Although Kawka & Vennes (2009) achieved a satisfactory fit to

the Balmer line profiles, their analysis did not consider a companion. We repeated that analysis using two composite model grids, DA+DC or DA+DA. We modelled the primary with a pure-hydrogen model grid (DA) and the secondary with either a pure-helium (DC) or a DA grid. First, we set the mass of the secondary to 0.75 \(M_\odot\). We fitted the Balmer line profiles (see Kawka & Vennes, 2009, for details of the NTT-EFOSC2 spectrum) varying three parameters: the temperature and surface gravity of the primary \((T_{\text{eff,p}}, \log g_p)\) and the effective temperature of the secondary \((T_{\text{eff,s}})\). The total flux was obtained by combining the primary and secondary surface fluxes weighted by the emitting area: \(R^2 f_{\text{obs}} = R_p^2 f_p + R_s^2 f_s\), where \(R\) is the effective radius of the composite star, and \(R_p\) and \(R_s\) are the primary and secondary radii computed using the evolutionary mass radius relations of Benvenuto & Althaus (1999) and Serenelli et al. (2002). Note that the flux composition takes into account the calculated orbital phase of the observed spectrum and the corresponding offset in velocities between the two stars. The combined spectrum is then fitted to the observed spectrum with \(\chi^2\) minimization techniques.

The best-fit parameters from the DA+DA grid are \(T_{\text{eff,p}} = 8580 \pm 50 \text{ K} (1\sigma)\) and \(\log g_p = 6.18 \pm 0.15\) for the primary and \(T_{\text{eff,s}} \leq 9600 \text{ K}\) for the secondary. The flux contribution from the secondary at 5500 Å (V-band) is \(\leq 5\%\) of the total flux. But if we used the DA+DC grid we obtained an upper limit of \(T_{\text{eff,s}} \leq 7200 \text{ K}\), with a flux contribution \(\leq 2\%\). Setting the secondary mass to \(1 M_\odot\) did not affect our solution for the primary, but allowed a higher secondary temperature (\(+400 \text{ K}\)). In summary, the best-fit parameters are identical to the single star solution obtained by Kawka & Vennes (2009), and we conclude that the secondary star is much fainter than the primary star.

4. Discussion

If the maximum mass of a white dwarf is \(1.35 M_\odot\), a white dwarf companion would be expected for inclinations \(i > 51^\circ\). Ultra-massive white dwarfs have been found to be either single or in close binary systems (Vennes & Kawka, 2008), as in the peculiar binary system RX J0648.0-4418 (Mereghetti et al., 2009). Constraining the secondary mass between 1.35 and 0.75 \(M_\odot\), the system is not expected to merge before 5.1 to 7.8 Gyr. In the low-mass range the merger would create an ultramassive white dwarf, while in the upper mass range the system would constitute a Type Ia supernova candidate.

Figure 3 shows the locus of the ELM binary systems in a period versus ELM mass diagram. The data from Table 3 are compared to the mass-period relations from the WD+NS binary evolutionary scenarios of Nelson et al. (2004) and Tauris & Savonije (1999). Similar trends are also predicted for the brighter star in binary systems with two white dwarf stars (Nelemans et al., 2001). Figure 3 also includes the long period WD+NS system PSR B0820+02 (Koester & Reimers, 2000). This particular system extends the apparent correlation toward higher mass (0.60 \(\pm 0.08 M_\odot\) and longer period (1232.5 d).

Table 3 first provides the parameters of NLTT11748, followed by the parameters of systems containing white dwarfs with a neutron star companion (NS+WD), and double white dwarf systems (WD+WD). Finally, we list the parameters of the possible
progenitors of ELM white dwarf binary systems. Some scatter between the mass of the brighter star and the orbital period is clearly visible, but a correlation is still observed between the two parameters. The models of (Tauris & Savonije 1999) appear to better represent the observed trend than those of Nelson et al. (2004). The two outstanding points that are significantly off the predicted relationship of either models are the two systems with very short periods (SDSSJ1053+5200, SDSSJ1436+5010: Kilic et al. 2010; Mullally et al. 2010). Overall, WD+WD and WD+NS systems overlap in the diagram, so this trend alone does not allow one to distinguish between WD+WD and WD+NS systems.

The ELM white dwarfs that are companions to neutron stars appear to be very faint (V > 20) with the brightest known ELM companion to a neutron star with an apparent magnitude of V = 19.6 (PSR J1012+5307). The binary systems containing an ELM white dwarf and either a confirmed or probable white dwarf companion are significantly brighter, with apparent visual magnitudes ranging from 16.5 up to 19.3, with NLTT 11748 the brightest of the sample. In terms of distances we find that the WD+WD sample lies within a range of 0.1-1.6 kpc at an average distance of 0.75 kpc, while the WD+NS sample lies within a range of 0.15-4.4 kpc at an average distance of 1.5 kpc. Located at a distance of 0.4 kpc and being the brightest known ELM, NLTT 11748 fits well within the relatively closer and brighter class of WD+WD systems. Moreover, NLTT 11748 is not associated with a known radio source, therefore based on these considerations alone we may conclude that the companion to NLTT 11748 is another white dwarf with a mass above average.

Indeed, after this work was submitted for publication, Steinfadt et al. (2010) announced the discovery of primary and secondary eclipses in NLTT 11748 confirming the secondary star as a white dwarf. Their analysis confirms the ELM nature of the primary star and corroborates our analysis of the binary properties. Their orbital period measurement, based on eclipse timing, agrees with our spectroscopic period within error bars. Finally, our ephemeris allows us to identify the primary and secondary eclipses observed by Steinfadt et al. (2010) with the corresponding orbital conjunctions.

5. Conclusions

We find that the ELM white dwarf NLTT 11748 is part of a short-period binary system (P = 5.64 hrs). Based on our orbital analysis alone, we find that the minimum mass of the companion is 0.75 M⊙. However, the companion has independently been identified as a faint white dwarf (Steinfadt et al. 2010), and assuming a mass of 0.75 M⊙, we constrained the companion temperature to ≤ 9600 K (DA) or ≤ 7200 K (DC). The kinematics of NLTT 11748 also place the system in the Galactic halo.

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Table 3. Confirmed binary systems containing a low-mass white dwarf.

| Name                  | P_orb (days) | MWD (M⊙) | Reference |
|-----------------------|--------------|-----------|-----------|
| NLTT 11748            | 0.2351       | 0.167 ± 0.005 | 1.2 |
| PSR1835+09            | 12.3272      | 0.258 ± 0.020 | 3 |
| PSR0437+4715          | 5.7410       | 0.254 ± 0.018 | 4 |
| PSR0218+4232          | 2.0288       | 0.275 ± 0.105 | 5.6 |
| PSRJ1909-3744         | 1.5334       | 0.204 ± 0.002 | 7 |
| PSRJ1911-5958A        | 0.8371       | 0.175 ± 0.010 | 8.9 |
| PSRJ1012+5307         | 0.6074       | 0.164 ± 0.027 | 10.1112 |
| PSRJ1738+0333         | 0.3548       | 0.20 ± 0.05 | 13 |
| PSRJ0751+1807         | 0.2631       | 0.191 ± 0.015 | 14 |

References.

(1) This work; (2) Kawka & Vennes (2009); (3) Kaspi et al. (1994); (4) Verbist et al. (2008); (5) Navarro et al. (1995); (6) Bassa et al. (2003); (7) Jacoby et al. (2005); (8) Corongiu et al. (2006); (9) Bassa et al. (2006); (10) Webb et al. (2004); (11) van Kerkwijk et al. (1998); (12) Callanan et al. (1998); (13) Freire et al. (2008); (14) Nice et al. (2005); (15) Vennes et al. (2009a); (16) Kilic et al. (2010); (17) Marsh et al. (2010); (18) Heber et al. (2006); (19) Archibald et al. (2009); (20) Wang et al. (2009).

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