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The evolution and masses of the neutron star and donor star in the high mass X-ray binary OAO 1657–415*

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ABSTRACT

We report near-infrared radial velocity measurements of the recently identified donor star in the high mass X-ray binary system OAO 1657–415 obtained in the H band using ISAAC on the VLT.

Cross-correlation methods were employed to construct a radial velocity curve with a semi-amplitude of 22.1 ± 3.5 km s^{-1}. Combined with other measured parameters of this system this provides a dynamically determined neutron star mass of $1.42{\pm}0.26$ M$_{\odot}$ and a mass of 14.3 ± 0.8 M$_{\odot}$ for the Ofpe/WN9 highly evolved donor star.

OAO 1657–415 is an eclipsing High Mass X-ray binary pulsar with the largest eccentricity and orbital period of any within its class. Of the ten known eclipsing X-ray binary pulsars OAO 1657–415 becomes the ninth with a dynamically determined neutron star mass solution and only the second in an eccentric system. Furthermore, the donor star in OAO 1657–415 is much more highly evolved than the majority of the supergiant donors in other High Mass X-ray binaries (HMXBs), joining a small but growing list of HMXBs donors with extensive hydrogen depleted atmospheres.

Considering the evolutionary development of OAO 1657–415, we have estimated the binding energy of the envelope of the mass donor and find that there is insufficient energy for the removal of the donor's envelope via spiral-in, ruling out a Common Envelope evolutionary scenario. With its non-zero eccentricity and relatively large orbital period the identification of a definitive evolutionary pathway for OAO 1657–415 remains problematic, we conclude by proposing two scenarios which may account for OAO 1657–415 current orbital configuration.

Key words: binaries:eclipsing - binaries:general - X-rays:binaries - stars:individual:OAO 1657–415 - stars:massive - stars:Wolf-Rayet

1 INTRODUCTION

1.1 Neutron star masses

Despite much theoretical work and the proposal of over 100 different neutron star (NS) equations of state (EoS) (Kaper et al. 2006), the precise form of the fundamental physical properties of matter under the extreme densities and pressures found within NS are still unknown. In this regard, observational data can help to eliminate contending EoS by rejecting those that place unreasonable constraints on the mass range of observed NS. The recent measurement of $1.97{\pm}0.04$ M$_{\odot}$ for the mass of the binary millisecond pulsar (MSP) PSR J1614-2230 already excludes many EoS invoking the presence of exotic hadronic matter (Demorest et al. 2010), while higher NS masses - albeit with greater uncertainty - have also been reported (see Section 6).

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Moreover, one might expect the mass of NSs to show a dependence on the prior evolutionary history, such that higher masses might be expected in binaries where significant accretion has occurred (e.g. binary MSPs) or where massive progenitors have yielded a high pre-SN core mass. With regard to the former, Zhang et al. (2011) have recently proposed that the mean mass of MSPs is greater than that of the total NS population, while Timmes et al. (1996) propose a bimodal distribution of NS masses (peaking at 1.27 & 1.76$M_\odot$) from Type II supernovae (SNe), with a reduced mass for NS resulting from Type Ib SNe (peaking at 1.32$M_\odot$) although, as noted by the authors, significant uncertainties in the input physics remain (e.g. pre SNe mass loss rates).

Unambiguous NS mass determinations in X-ray binaries can only be made for *eclipsing* binary systems, where the inclination angle is well constrained. In this paper we aim to derive masses for both components of the massive eclipsing X-ray binary OAO 1657–415, rendered possible by a combination of X-ray timing analysis for the NS and radial velocity (RV) analysis of the mass donor. The relative scarcity of X-ray pulsars, combined with the low geometric probability that an eclipse of the binary system will be seen, means that only 11 eclipsing X-ray binary pulsars are currently known. Up to this time 7 of these systems have NS mass determinations (e.g. Mason et al. (2010), Val Baker et al. (2005), Quaintrell et al. (2003)). The NS mass resolution of the remaining systems is thus a priority.

1.2 The history of OAO 1657–415

OAO 1657–415 was first detected over 30 years ago by the *Copernicus* X-ray satellite (Polidan et al. 1978). Follow up observations by *HEAO-1* detected pulsations with a period of 38.22 s (White & Pravdo 1979), whilst later observations by the *Compton Gamma-Ray Observatory* (CGRO) BATSE instrument determined that OAO 1657–415 was an eclipsing accreting pulsar with an orbital period of $\sim$ 10.44 days (Chakrabarty et al. 1993). Along with Vela X-1 (Quaintrell et al. 2003), OAO 1657–415 is one of only two eclipsing X-ray binary pulsars to exhibit a significant eccentricity, namely $e = 0.107 \pm 0.001$ (Jenke et al. 2011). It is further differentiated in possessing the longest orbital period (refined by Barnstedt et al. (2008) as $P = 10.448$ d) of any of these types of eclipsing X-ray binary systems.

From an initial examination of the orbital parameters of the X-ray pulsar it was determined that OAO 1657–415 was a high-mass system, indicating the mass of the donor lay in the range $14 - 18$ $M_\odot$, with a corresponding radius range of $25 - 32$ $R_\odot$. Determination of these stellar parameters led to a spectral classification of B0-6I (Chakrabarty et al. 1993).

The correct identification of the donor in this system required the precise location of OAO 1657–415 to be accurately made. This was achieved by the *Chandra X-Ray Observatory* narrowing the X-ray location error radius down to 0.5″. Optical imaging of this position did not detect any donor candidates down to a magnitude of V>23, implying many orders of optical extinction for the presumed massive mass donor. Near infrared imaging was therefore employed, resulting in the identification of a donor located within the *Chandra* error radius. A corresponding IR counterpart was located in the *2MASS* catalogue, namely 2MASS J17004888–4139214 with magnitudes J = 14.1, H = 11.7 and $K_s = 10.4$, an extinction of $A_V = 20.4 \pm 1.3$, and located at a distance of 6.4 ± 1.5 kpc (Chakrabarty et al. 2002).

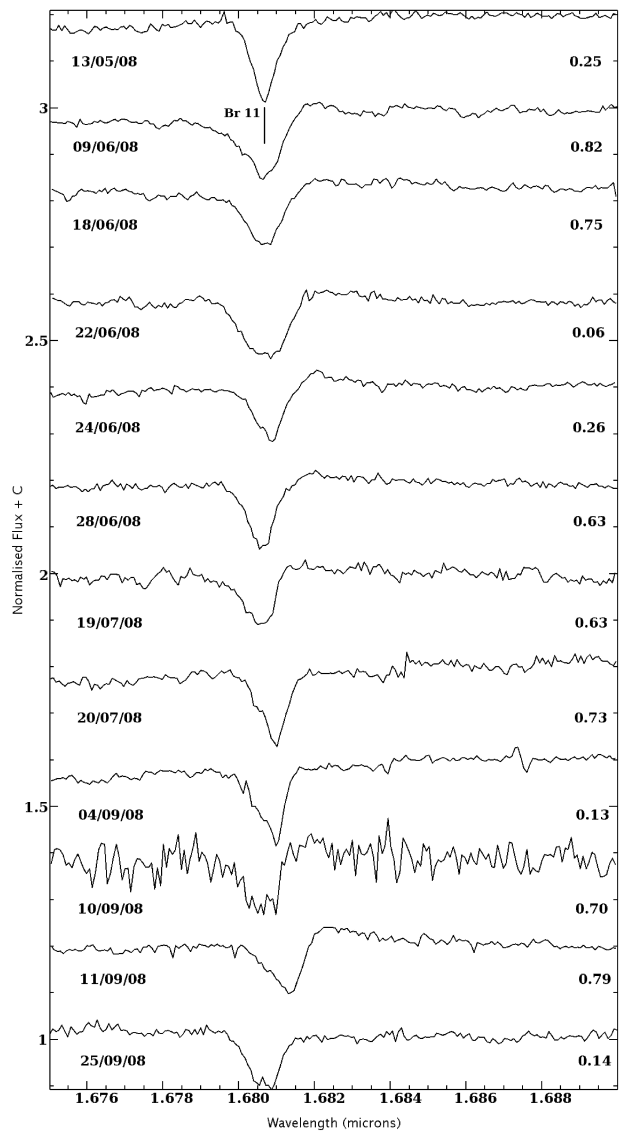

Figure 1. Continuum normalised H band spectra of OAO 1657–415 (highlighting the Brackett 11 line) in date order. The orbital phase corresponding to each spectrum is indicated on the right hand side of the figure.

As a result, near-IR spectroscopy proved mandatory to both classify the mass donor in OAO 1657–415 and also to construct an RV curve. Spectroscopy of the donor obtained in 2008 (Mason et al. 2009) led to a re-evaluation of the spectral classification, with the correspondence between published NIR B0-6 spectra (Hanson et al. 2005) and that of OAO 1657–415 proving poor. Close examination revealed that OAO 1657–415 shared a similar spectral morphology with that of Ofpe/WNL stars. These are stars in transition between the OB main sequence and hydrogen depleted Wolf-Rayet stars, whose evolution follows from a wide range of progenitor masses.

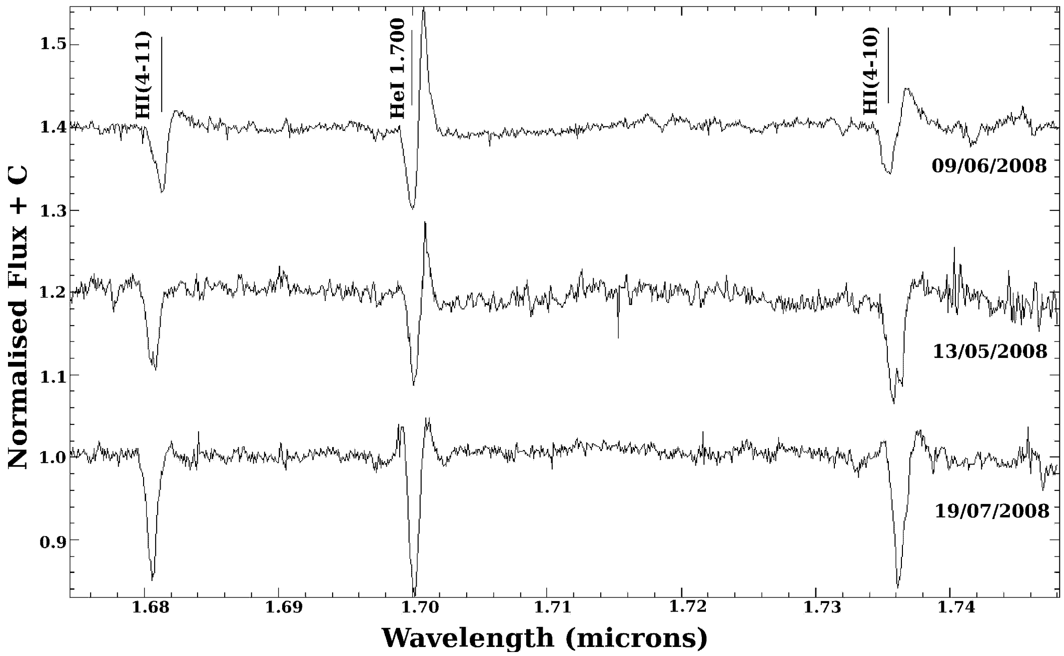

Figure 2. OAO 1657–415 spectral features illustrating the varying wind structure which is particularly noticeable in the P-Cygni line profile of the He I 1.700 μm line.

2 OBSERVATIONS AND DATA REDUCTION

As the mass donor in OAO 1657–415 is faint (H $\sim$ 11.7) we employed the NIR spectrometer ISAAC on the VLT to obtain high resolution (R $\sim$ 3000) and high S/N spectra in the H band. Observations were conducted between 2008 May 13th and 2008 September 25th in the SW MRes mode with a $0.8''$ slit. Science and RV template exposures centred on 1.7 μm for a total integration time of 1200s and 128s respectively were obtained. Spectra were reduced using the ISAAC pipeline and wavelength calibration performed utilising OH skylines.The resulting data has a count rate below 10 000 ADU; therefore no correction for non-linearity was required.

The RV template observed was HD154313, a bright (H $\sim$ 6.8) standard with a known radial velocity of -29 km s^{-1} and close in spectral type (B0Iab) to the previously assumed classification of OAO 1657–415 (Chakrabarty et al. 1993). Telluric correction was employed to remove atmospheric features from the target and template spectra.

Cross-correlation was performed using the standard IRAF[1] routine *fxcor*. Unfortunately due to time constraints and the end of the VLT observing semester we were unable to obtain the full data set of the 20 target spectra we requested. However, 12 high quality spectra that covered a wide range of orbital phase were obtained, sufficient to determine a dynamical mass solution for OAO 1657–415 (Fig. 1).

[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

3 DATA ANALYSIS

After telluric correction the target spectra can be seen to exhibit three well defined spectral lines: 1.681 μm Brackett 11 H I (4-11), 1.700 μm He I and 1.736 μm Brackett 10 H I (4-10) (Fig. 2). As noted earlier, OAO 1657–415 has been spectrally classified as an Ofpe/WNL star. These transitional stars are characterised by exceptionally intense stellar winds with low terminal velocities and high mass loss rates (Martins et al. 2007). This is demonstrated in the morphology of the three spectra from the dataset obtained at differing orbital phases (Fig. 2), in which P-Cygni profiles can be seen in each of the spectral lines, the intensity of which clearly varies throughout an orbital cycle.

Stellar wind contamination leading to varying line-profiles make the process of cross-correlation to determine radial velocities problematic. After close examination of each spectrum within the dataset it was decided to cross-correlate around the region surrounding the Brackett 11 1.681 μm line. We determined that the measured radial velocities of this line would be less affected by the stellar wind, originating closer to the photosphere and exhibiting less P-Cygni profile variation. Unfortunately for two of the science spectra (#1 and #12 in Table 1) RV template observations were not completed. Additionally 2 science spectra (#3 and #9 in Table 1) exhibited significantly broadened line-profiles in comparison to other spectra in the dataset. To achieve as accurate an RV measurement as possible it was decided to use the science spectrum #2 as a template reference spectrum in these four cases. We determined this spectrum possessed the most accurate telluric division and the narrowest line profile. The resulting radial velocities were then corrected to the solar system barycentre and are shown in Table 1.

Table 1. The radial velocities of OAO 1657–415 determined from the Brackett 11 absorption line.

Spectrum number	Mid-point of Observations (UT)	MJD	Phase	True anomaly	Radial velocity / km s^{-1}	RV Std
1	2008 May 13.340	54 599.41	0.249	0.283	–45.77 ± 10.3	Reference
2	2008 Jun 09.022	54 626.22	0.815	0.783	–99.05 ± 10.3	HD154313
3	2008 Jun 18.928	54 636.00	0.751	0.718	–79.26 ± 10.3	Reference
4	2008 Jun 22.238	54 639.24	0.061	0.075	–39.93 ± 10.3	HD154313
5	2008 Jun 24.319	54 641.32	0.260	0.293	–26.02 ± 10.3	HD154313
6	2008 Jun 28.149	54 645.15	0.627	0.605	–65.87 ± 10.3	HD154313
7	2008 Jul 19.115	54 666.06	0.628	0.606	–66.72 ± 10.3	HD154313
8	2008 Jul 20.076	54 667.08	0.725	0.694	–61.13 ± 10.3	HD154313
9	2008 Sept 04.066	54 713.07	0.127	0.153	–38.67 ± 10.3	Reference
10	2008 Sept 10.054	54 719.05	0.700	0.670	–79.50 ± 10.3	HD154313
11	2008 Sept 11.013	54 720.01	0.792	0.759	–81.77 ± 10.3	HD154313
12	2008 Sept 25.110	54 734.11	0.141	0.169	–45.52 ± 10.3	Reference

4 OAO 1657–415 RV CURVE FITTING

From X-ray data it has been deduced that OAO 1657–415 has an elliptical orbit with $e = 0.107 \pm 0.001$ (Jenke et al. 2011) and the linear ephemeris of Barnstedt et al. (2008) gives the epoch at which the mean longitude is 90° as

$$T_{90}/\mathrm{MJD} = 52663.893(10) + 10.44812(13)N \quad (1)$$

where the uncertainties refer to the last decimal place quoted and N is the cycle number. The more recent quadratic ephemeris derived by Jenke et al. (2011) concludes that the orbital period is currently decreasing with $\dot{P}_{\mathrm{orb}}/P_{\mathrm{orb}} = (-3.34 \pm 0.14) \times 10^{-6}\ \mathrm{yr}^{-1}$, but otherwise is very little different from this. Given the relatively low precision of our radial velocity measurements, the linear ephemeris is perfectly adequate for our purposes. During the period in which our observations were conducted the accumulated uncertainty in phase was calculated as ~ 0.003.

As OAO 1657–415 has an appreciable eccentricity and thus will significantly deviate from sinusoidal motion, we cannot fit the radial velocities of the donor in this system with a sinusoidal radial velocity curve. For an eccentric system we can construct a sinusoidal radial velocity curve by fitting the true anomaly ν (the angle between the major axis and a line from the star to the focus of the ellipse) to the calculated radial velocities of the donor. In order to do this we must first deduce the mean anomaly M (the time since the last periapsis multiplied by the orbital phase). This in turn is related to the eccentric anomaly E (the angle between the major axis of the ellipse and the line joining the position of the object and the centre of the ellipse) by the equation

$$E - e \sin E = M = \frac{2\pi}{P}(t - T_0) \quad (2)$$

The right hand side of the above equation is the orbital phase, with T_0 the time of periastron passage. In an eccentric orbit, T_0 and T_{90} are related by

$$T_0 = T_{90} + \frac{P(\omega - \pi/2)}{2\pi} \quad (3)$$

In the case of OAO 1657–415, the longitude of periastron, $\omega = 91.7^\circ \pm 0.5^\circ$ (Jenke et al. 2011), so the offset between the two is only about 0.005 in orbital phase.

This eccentric anomaly equation cannot be solved analytically, but solving it numerically we obtained the eccentric anomaly for each observation. These eccentric anomaly values can then be finally related to the true anomaly by the equation

$$\tan\left(\frac{\nu}{2}\right) = \left(\frac{1+e}{1-e}\right)^{\frac{1}{2}} \tan\left(\frac{E}{2}\right) \quad (4)$$

The calculated true anomaly values are shown in Table 1 and the measured radial velocities plotted as a function of the calculated true anomaly are shown in Figure 3. Over-plotted on these data are two sinusoidal fits. The first has just two free parameters (RV amplitude and systemic velocity) with a period and zero phase fixed by the ephemeris of Barnstedt et al. (2008). The second fit allows the zero phase as a third free parameter to allow for any possible accumulated uncertainty. However, this is only a marginally better fit and the reduction in chi-squared does not justify the inclusion of an extra free parameter. We therefore use the first fit which yields a radial velocity amplitude of 22.1 ± 3.5 km s^{-1} and a systemic velocity of 57.2 ± 3.0 km s^{-1}. Error bars on each radial velocity value shown in Figure 3 are such that the reduced chi-squared of the fit is equal to unity.

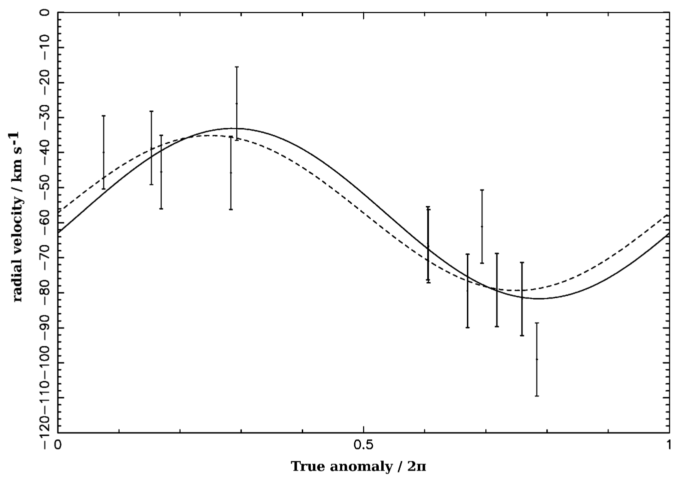

Figure 3. Radial velocity solution for the mass donor in OAO 1657–415. The dashed line represents a fixed zero phase coincident with the published ephemeris (Barnstedt et al. (2008)). The solid line is the best fitting sinusoid with three free parameters, allowing for a shift in phase.

5 CALCULATION OF SYSTEM PARAMETERS

Jenke et al (2011) measured the projected semi-major axis of the neutron star's orbit from X-ray pulse timing delays as $a_x \sin i = 106.16 \pm 0.08$ light seconds. From this, the semi-amplitude of the neutron star's radial velocity may be calculated using

$$a_X \sin i = \left(\frac{P}{2\pi}\right) K_X (1 - e^2)^{1/2} \quad (5)$$

to give $K_X = 222.8 \pm 0.2$ km s^{-1}.

To determine the masses of the system components we must first consider the mass ratio of the system q which is equal to the ratio of the semi-amplitudes of the radial velocities for each star

$$q = \frac{M_X}{M_O} = \frac{K_O}{K_X} \quad (6)$$

where M_O and M_X are the masses of the supergiant star and neutron star respectively, with K_O and K_X the corresponding semi-amplitudes of their radial velocities. Specifically for elliptical orbits,

$$M_O = \frac{{K_X}^3 P \,(1 - e)^{\frac{3}{2}}}{2\pi G \sin^3 i} \,(1 + q)^2 \quad (7)$$

and similarly

$$M_X = \frac{{K_O}^3 P \,(1 - e)^{\frac{3}{2}}}{2\pi G \sin^3 i} \left(1 + \frac{1}{q}\right)^2 \quad (8)$$

where i is the angle between the normal to the plane of the orbit and the line-of-sight and P is the orbital period.

The geometry of the eclipse yields the following relation between the angle of inclination of the system, i, the eclipse half angle, θ, and various length scales in the system:

$$\sin i \approx \frac{\left[1 - \beta^2 \left(\frac{R_L}{r}\right)^2\right]^{1/2}}{\cos\ \theta_e} \quad (9)$$

Here R_L is the Roche lobe radius of the supergiant, r is the separation between the centres of the two stars and β is the ratio of the supergiant's radius to that of its Roche lobe, referred to as the filling factor. For stars in a circular orbit, R_L and β are constant, and the separation between the centres of the two stars is just the radius of the orbit. An approximation of the Roche lobe radius is given by Joss & Rappaport (1984) as

$$\frac{R_L}{r} \approx A + B \log q + C \log^2 q \quad (10)$$

where they determine the constants as

$$A \approx 0.398 - 0.026\Omega^2 + 0.004\Omega^3 \quad (11)$$

$$B \approx -0.264 + 0.052\Omega^2 - 0.015\Omega^3 \quad (12)$$

$$C \approx -0.023 - 0.005\Omega^2 \quad (13)$$

Ω is the ratio of the spin period of the supergiant to its orbital period. Since the system has not circularized, Ω is unlikely to be unity. If tides are efficient, then we might suppose that the rotation of the donor is synchronized at periastron, where the tides are most effective. In this case, the star's angular velocity will be larger than the orbital velocity at mid-eclipse, and at this point $\Omega \sim 1.2$. To account for this uncertainty in our calculations we therefore adopt $\Omega = 1.2 \pm 0.2$ as a conservative estimate.

For systems with a significantly eccentric orbit such as OAO1657–415, the Roche lobe radius, the separation between the centres of mass of the two stars, and the Roche lobe filling factor will all vary with orbital phase, although R_L/r can be assumed to be constant. Using the above, we therefore calculate $R_L/r = 0.553 \pm 0.025$.

The remaining system parameters were then calculated under two assumptions. If the donor star fills its Roche lobe at periastron, then the filling factor at mid-eclipse will be $\beta \sim 0.9$. This allows us to calculate a lower limit to the system inclination, i, and upper limits are arrived at for the stellar masses. Conversely, if the system is viewed edge-on ($i = 90°$), we calculate a lower limit for the Roche lobe filling factor, β at mid-eclipse, and lower limits are derived for the stellar masses. The limits on the semi-major axis of the orbit, a, are simply determined from Kepler's third law using the calculated ranges for the masses of the two stars. In practice, it turns out that the uncertainties on the system parameters overlap significantly for these two limits, so in Table 2 we list a single set of values.

Now, the separation between the centres of the two stars at mid-eclipse is given by

$$r = \frac{a(1 - e^2)}{1 + e \cos\omega} \quad (14)$$

where ω is the argument of periastron, measured by Jenke et al (2011) to be $\omega = 91.7° \pm 0.5°$ in this case. This yields a value of $r = 49.9 \pm 1.0$ $R_\odot$. Then the Roche lobe radius, R_L, is this separation multiplied by the factor 0.553 ± 0.025 calculated earlier, which gives the value listed in Table 2. Finally, the radius of the donor star, R_O is just βR_L, and this value is also shown in Table 2.

Uncertainties on each of the inferred system parameters shown in Table 2 were determined by a Monte-Carlo calculation which propagated the uncertainties in each observed parameter through one million trials, assuming a Gaussian distribution in each individual uncertainty.

6 DISCUSSION

6.1 System properties

The H band spectra for the period May - July, 2008 (Fig. 2) demonstrate a high degree of line profile variability (LPV) in the H I transitions, with the H I (4-10) line observed to transition from absorption to a P Cygni profile. He I 1.70 μm is also present and displays a variable P Cygni profile, although He II 1.69μm is absent. Conversely, the K band spectrum of this object previously published (Fig 2. Mason et al. (2009)), presents the He II 2.189 μm line in emission. The H band spectrum is more reminiscent of P Cygni early B hypergiants than the Ofpe/WNL classification that had been inferred from the K band data alone. Indeed, the H and K spectra can only be reconciled if it is assumed that the He II 2.189 μm transition is driven into emission by the presence of the neutron star.

Precedents for excess He II emission in HMXBs in both the optical and near-IR are provided by LMC X-3 & X-4 (Negueruela & Coe 2002) and CI Cam (Clark et al. 1999) respectively. Radial velocity shifts in this line in LMC X-4 confirm its association with the compact accretor, with the observed line strength variability possibly resulting

Table 2. System parameters for OAO 1657–415.

Parameter	Value	Ref.
Observed		
$a_X \sin i$ / lt sec	106.16 ± 0.08	[1]
P / d	10.44812 ± 0.00013	[2]
T_{90} / MJD	52663.893 ± 0.001	[2]
ω	91.7 ± 0.5	[1]
e	0.107 ± 0.001	[1]
θ_e / deg	29.7 ± 1.3	[3]
K_O / km s^{-1}	22.1 ± 3.5	[4]
Assumed		
Ω	1.2 ± 0.2	
Inferred		
K_X / km s^{-1}	222.8 ± 0.2	
q	0.099 ± 0.016	
β	0.896 ± 0.051	
i / deg	87.0 ± 7.7	
M_X / M$_\odot$	1.42 ± 0.26	
M_O / M$_\odot$	14.3 ± 0.8	
a / R$_\odot$	50.3 ± 1.0	
R_L / R$_\odot$	27.6 ± 1.6	
R_O / R$_\odot$	24.8 ± 1.5	

[1] Jenke et al. 2011; [2] Barnstedt et al. 2008;
[3] Chakrabarty et al. 1993; [4] this paper

from changes in accretion rate; similar observations for OAO 1657–415 would test the hypothesis that the line is likewise associated with the accretor rather than the primary. The significant rapid, non-secular LPV in the remaining H I and He I lines is most easily understood by a departure from spherical symmetry by the presence of the neutron star. The WNLh star Wd1-44 provides a precedent for this conclusion, also demonstrating dramatic LPV in wind dominated H I and He I P Cygni profiles, although in this case it is expected that the companion is a normal H/He-burning object (Clark et al. 2010).

Mindful of the above, we attempted to derive the physical and wind properties of the donor star in OAO 1657–415 using the stellar atmosphere modelling code CMFGEN (Hillier & Miller 1998) and the method as described in Section 4.1 of Crowther & Evans (2009), utilising the H and K band spectra obtained between May - September 2008. Unfortunately, we were unable to obtain a satisfactory formal fit to these data, which we attribute to the reasons above, namely a lack of contemporaneous data for a star showing LPV - possibly as a consequence of an aspherical wind - and the presence of an additional source of ionising radiation within the system yielding discrepant He II 2.189 μm emission.

While we were unable to obtain a formal fit to the model, we were able to determine order of magnitude estimates for the bulk properties of the star that we regard as indicative of its true properties: $T \sim 20$ kK, $L \sim 10^{5.1}$L$_\odot$, $R \sim 30$ R$_\odot$, $\dot{M} = 2 \times 10^{-6}$ M$_\odot$ yr^{-1}, $v_\infty \sim 250$ km s^{-1}. Using our spectra from the H and K bands the model also provided us with estimates of the mass fraction of hydrogen $X_H = 5\%$ (H/He = 0.21 by number) in which our primary diagnostics were the Brackett series lines (1.680, 1.736 and 2.166 μm), helium $X_{He} = 94\%$ by mass from He I lines (1.700, 2.058, 2.112, 2.161 μm) and other metals $X_Z = 1\%$.

Comparing the stellar parameters of OAO 1657–415 with the Ofpe/WNL star AF (Martins et al. 2007), we find a correspondence between temperature and radius, whilst the luminosity of OAO 1657–415 ($L \sim 10^{5.1}$L$_\odot$) is consistent within the uncertainties to that of AF. However, the lower than expected luminosity of OAO 1657-415 implies that it could be a B supergiant rather than a Ofpe/WNL star. Noting that there is a large degree of overlap between model derived luminosities of Ofpe/WNL and B supergiants, we turn to other stellar properties to address this possibility. We find the low terminal velocity of OAO 1657–415 combined with its mass loss rate and temperature are incompatible with those found for field Blue Supergiants (Crowther et al. 2006). B supergiants with a luminosity of $L \sim 10^{5.1}$L$_\odot$ would be expected to have a radius greatly in excess of that found from both modelling and dynamical calculations of ~ 30 M$_\odot$ (Searle et al. 2008). B supergiants also have a significantly greater hydrogen abundance of H/He = 5 by number (Crowther et al. 2006) than that found during our modelling of OAO 1657–415. With the degree to which hydrogen is depleted within OAO 1657-415 its radius may seem excessively large. However, several examples of WNL stars with atmospheres with a similar or greater degree of hydrogen depletion and comparable radii to that of OAO 1657-415 have been detailed in the literature. In particular, the emission line star HD 326823 (Marcolino et al. 2007) is reported as entering the Wolf-Rayet phase as a WN8 star with a radius R = 30 R$_\odot$ and a hydrogen mass fraction of $X_H \sim 3\%$. Similarly the WN8 star WR123 (Crowther et al. 1995) may have a hydrogen mass faction as low as 0.5% yet is reported as having a radius R $\sim$ 15 R$_\odot$.

6.2 OAO 1657–415 in an evolutionary context

When these properties are combined with the finding that OAO 1657–415 possesses a severely H-depleted atmosphere, it is apparent that it is a rather evolved object and is clearly more advanced than the typical OB SG mass donors in HMXBs. A comparable mass donor in this regard is Wray 977, the blue hypergiant companion within GX301-2. Prior to OAO 1657–415, Wray 977 was the most evolved non-WR donor known within a HMXB system. Wray 977 has a significantly higher hydrogen mass fraction of 45%, (Table 8 in Kaper et al. (2006)) than that of OAO1657–415.

Thus, while a definitive spectral classification for the mass donor in OAO 1657–415 is difficult, even if it has yet to formally become a WR star, it is apparent that it will do so shortly. As such it will become only the fourth known HMXB with such an evolved mass donor. The only other example in our Galaxy is Cyg X-3, which has a WNE mass donor orbiting a NS or BH companion in a 4.8 hr orbit (van Kerkwijk et al. 1996). van den Heuvel & De Loore (1973) describe an evolutionary scenario for this system, whereby the mass donor in the OB SG+accretor progenitor system expands towards a RSG phase, triggering Common Envelope evolution which leads to the formation of the WNE star and a dramatic contraction in orbital separation.

In contrast, while the two known extragalactic examples - IC10 X-1 (Clark & Crowther 2004) and NGC300 X-1 (Crowther et al. 2007) - also host WN stars, they both have significantly longer orbital periods ($\sim$ 30 hrs), and appear to host more luminous mass donors and more massive accretors[2]. These properties preclude these binaries from evolving via the scheme inferred for Cyg X-3. Instead, it is thought that they must have evolved from very compact initial O+O star binaries via the case M pathway described by de Mink et al. (2009). In this, the rapid rotation of both (tidally locked) components leads to efficient mixing and hence homogeneous chemical evolution, which results in the stars remaining within their Roche lobes while evolving to WR stars. This evolution prevents binary driven mass loss, resulting in a longer final orbital period and crucially a heavier relativistic companion.

However, the properties of OAO 1657-415 do not fit either of these schemes. The non-zero eccentricity appears to preclude post-SN common envelope evolution (as a result of circularization processes during spiral-in) and hence OAO 1657-415 being the endpoint of the van den Heuvel & De Loore (1973) pathway. To address this in a more quantitative manner we adopt the formalism of Dewi & Tauris (2000), whereby the evolution of a putative RSG+NS system through a common envelope (CE) phase may be followed by the paramerisation of the binding energy of the envelope of the donor star (λ) and the efficiency parameter η for the removal of the envelope during spiral-in. In the following discussion we assumed an initial donor mass of $\sim 40\,M_{\odot}$ resulting in a $\sim 24.5\,M_{\odot}$ envelope and $\sim 15.5\,M_{\odot}$ core, representative of the current mass of the Ofpe/WNL star. The binding energy of the envelope of the mass donor is given by

$$E_{\rm bind} = \frac{-GM_{\rm donor}M_{\rm env}}{\lambda R_{\rm donor}} \tag{15}$$

where $M_{\rm donor}$, $M_{\rm env}$ and $R_{\rm donor}$ are the masses of the donor and envelope of the donor and the donor radius, respectively. In order to facilitate a successful ejection of the donor star envelope we consider a wide orbit prior to the CE for two reasons: A wide orbit requires an evolved donor star to fill its Roche-lobe and giant stars have relatively small binding energies of their envelope. Furthermore, a wide pre-CE orbit has the potential to release more orbital energy during spiral-in. Even for a rather evolved donor ($R_{\rm donor} \simeq 1500\,R_{\odot}$) we find $|E_{\rm bind}| \sim 10^{50}$ erg given that for such a star $\lambda \leqslant 0.02$ (c.f. Dewi & Tauris (2001)). However, simply determining the available orbital energy:

$$\Delta E_{\rm orb} = \frac{GM_{\rm core}M_{\rm NS}}{2a} - \frac{GM_{\rm donor}M_{\rm NS}}{2a_0} = 8.2\times 10^{47}{\rm erg} \tag{16}$$

where the mass of the neutron star, $M_{\rm NS} = 1.5\,M_{\odot}$ and a_0 and a are the initial and final orbital separations. Thus even assuming the smallest possible envelope binding energy and a 100% ejection efficiency ($\eta = 1.0$) for conversion of orbital energy we find that there is insufficient energy available for ejection of the donor envelope (by 2 orders of magnitude). This is indicated graphically in Fig. 4 which demonstrates that for a successful ejection of the envelope yielding the current orbital parameters one would require $\lambda > 1$ (solutions are only possible above the dashed line), while stellar structure calculations for a $40\,M_{\odot}$ star yield $\lambda = 0.006-0.02$ (Dewi & Tauris 2001).

[2] $> 15{\rm M}_{\odot}$ for NGC300 X-1 ((Crowther et al. 2010)) and $> 23{\rm M}_{\odot}$ for IC10 X-1 ((Silverman & Filippenko 2008)) versus $< 10{\rm M}_{\odot}$ for Cyg X-3 ((Hanson et al. 1999)).

If the common envelope evolutionary pathway of van den Heuvel & De Loore (1973) cannot produce OAO1657–415 what might? The large degree of H-depletion in the mass donor implies a post-rather than pre-RSG state; hence it is difficult to interpret the system as evolving *towards* such a common envelope phase. Moreover, case M chemically homogeneous evolution (e.g. de Mink et al. (2009)) also seems inappropriate since it would result in a much more massive relativistic companion than we find.

In the absence of any tailored numerical model for the evolution of OAO 1657–415 (c.f. Wellstein & Langer (1999a) for GX301-2) any scenario is inevitably somewhat speculative. It might be supposed that the progenitor system consisted of two O stars in a comparatively short orbit. Mass is transferred from the primary to the secondary, which after rapidly gaining mass evolves more quickly than the donor and hence undergoes SNe first, leaving the primary in a H depleted phase. Despite such mass transfer leading to a rather wide pre-SN binary configuration, a fortuitous SN kick may reduce the separation, with subsequent interaction acting to circularise the orbit. While this would leave the primary in the requisite H-depleted state, simulations of conservative mass transfer (e.g. Wellstein et al. (2001)) leading to reverse SNe yield very low masses for the mass donor in comparison to our dynamical mass estimate. Alternatively, from our earlier paper on OAO1657–415, (Mason et al. 2009) luminosity calculations and comparison to evolutionary tracks for massive stars from Meynet & Maeder (2000) indicate a progenitor mass for the OAO1657–415 donor of $\sim 40M_{\odot}$. This implies OAO1657–415 is massive enough to have undergone an LBV phase (Langer et al. 1994). If the evolution of the progenitor system had proceeded such that a LBV+NS was produced with an orbital period in which both components would interact during the LBV phase, in this case the binding energy of the donors envelope would be reduced whilst the corresponding efficiency parameter η for the removal of the envelope would increase. The changes to these parameters might be sufficient to enable the removal of the donors envelope by common envelope evolution. This scenario has been suggested qualitatively by De Donder et al. (1997). The hydrogen depleted HMXB system GX301-2 which hosts a blue hypergiant donor of $43M_{\odot} \pm 10M_{\odot}$ with a $1.85 \pm 08M_{\odot}$ NS companion in an eccentric 41d orbit may provide an analogue to the progenitor system to OAO1657–415. Modelling of this system by Wellstein & Langer (1999b) as a $25+26M_{\odot}$ binary which undergoes conservative case A mass transfer with an initial 3.5 day period was able to reproduce the current observed mass of the donor successfully, demonstrating that it is possible for a massive hypergiant to have a NS companion.

We are thus currently unable to determine a definitive qualitative evolutionary pathway for OAO 1657–415, but conclude that it cannot have formed via either of the scenarios proposed for the other three known WR X-ray binaries - consequently this class of object appear to be rather heterogeneous in nature in comparison to other subsets of HMXB such as the OB SG and Be star X-ray binaries.

However we do note that the future evolution of the mass donor in OAO 1657–415 will result in an increase in wind velocity, while wind driven mass loss will cause the separation to increase. The combination of both effects will result in a reduction in accretion efficiency and hence X-ray

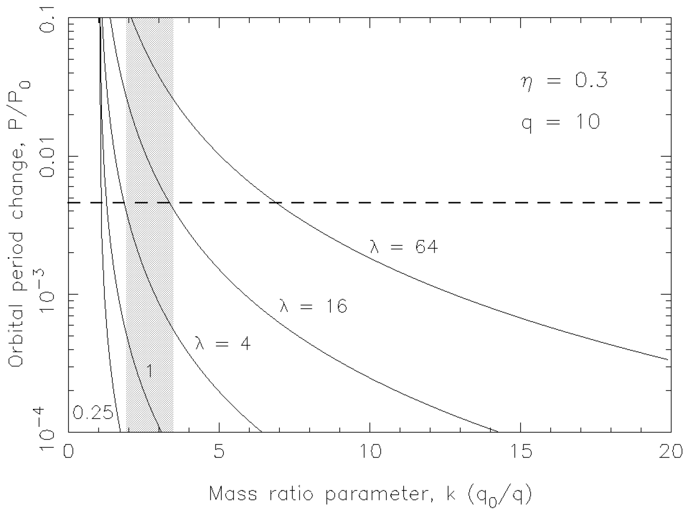

Figure 4. Plot of the initial/final mass ratio (in this case q is defined as $M_{\rm core}/M_{\rm NS}$), $k(=q_0/q)$, versus the change in the orbital period - P/P_0. The dashed line represents the value of the latter assuming a maximum orbital separation of $\sim$ 2500 $R_\odot$ (P_0 = 2250 days), while the shaded region corresponds to the range valid for k. The curved lines represent different binding energies of the envelope of the donor star (λ), assuming $q = 10$ and an ejection efficiency $\eta = 0.3$. See Sect 6.2

luminosity. Hence one might suppose that even if the evolutionary pathway that formed OAO1657–415 is traversed by large numbers of stars, comparatively few will be detectable as X-ray sources due to the likely rapidity of passage through the Ofpe/WNL phase.

6.3 Future evolution of OAO 1657-415

The final mass of the Wolf-Rayet star prior to its core-collapse is probably somewhere between $5 - 10\,M_\odot$ (Meynet & Maeder 2005). If the star loses its mass in the form of a direct fast wind, (assuming the vast majority of the mass is lost from the binary) the system will have an orbital period of more than 65 days when the companion is reduced to $5\,M_\odot$ prior to the collapse in less than 1 Myr. If the outcome of the core collapse is a neutron star then the ejection of the envelope surrounding the iron core is likely to disrupt the binary; a binary will be disrupted if it loses more than half of its total mass in an instantaneous event like a supernova (Colgate 1970). On the other hand, the momentum kick expected to be imparted to the newborn neutron star (Lyne & Lorimer 1994) can also, depending on its direction, have the effect of tightening the binary so it survives and remains bound despite losing more than half of its total mass (Hills 1983). In this case a double neutron star system is formed and would most likely be wider than the widest of the currently 9 double neutron star systems known in our Galaxy, PSR J1811-1736, which has an orbital period of 18.8 days.

7 CONCLUSIONS

Following on from the recent spectral classification of the High Mass eclipsing X-ray binary pulsar OAO 1657–415 (Mason et al. 2009), we have reported the analysis and results from multi-epoch observations of the object using the ESO/VLT NIR spectrograph ISAAC. We have constructed an orbital solution from the measured radial velocities which, combined with the orbital parameters of this eccentric system, provides a dynamically determined neutron star mass of 1.42 ± 0.26 $M_\odot$. The donor star in this system was previously determined to be of type Ofpe/WN9, that has experienced a significant degree of mass loss. The radial velocity curve constructed showed that the donor mass lies within the range 14.3 ± 0.8 $M_\odot$.

An attempt was made to model the stellar atmosphere of the donor; this was found to be problematic due to the presence of He II emission that made a formal fit to the spectrum difficult. Modelling of the stellar atmosphere did however provide order of magnitude estimates of stellar parameters, indicating that the Ofpe/WN9 star in this system, although significantly hydrogen depleted, has retained a small fraction of its envelope. This combined with the non-zero eccentricity and $\sim$ 10 day orbital period of the system is indicative of a different evolutionary pathway than in the three other WR-CC systems known. Calculating the binding energy of the envelope we found there is insufficient energy to eject the envelope. This combined with the orbital period of the system effectively rules out Common Envelope evolution as a viable evolutionary scenario. We have postulated other evolutionary pathways for OAO 1657–415 in which mass transfer occurs in a short binary orbit in which the secondary is the first to experience a SNe, or the system experiences a 'mild' form of CE evolution during an LBV phase. Whilst we are unsure of the exact evolutionary process responsible for the current configuration of OAO 1657–415, we are convinced that the evolution of this system forms an entirely new evolutionary scenario than the two proposed to explain the development of the other three known Wolf-Rayet X-binary systems.

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